Report No. CG-D-08-98

U.S. Coast Guard/U.S. Maritime Administration
Cooperative Research on Marine Engine Exhaust

Final Summary Report on Project 3310
Marine Diesel Exhaust Emissions (Alternative Fuels)

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FINAL REPORT
September 1997

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National Technical Information Service, Springfield, Virginia 22161

Prepared for:

U.S. Department of Transportation
United States Coast Guard
Systems, (G-S)
Washington, DC 20593-0001

and

U.S. Coast Guard
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Technical Report Documentation Page

1. Report No. CG-D-08-98	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle U.S. Coast Guard/U.S. Maritime Administration Cooperative Research on Marine Engine Exhaust Emissions **Final Summary Report on Project 3310, Marine Diesel Exhaust Emissions (Alternative Fuels)**		5. Report Date September 1997 6. Performing Organization Code Project No. 3310.1
7. Author(s) Alan P. Bentz		8. Performing Organization Report No. R&DC 29/97
9. Performing Organization Name and Address JBL Associates, Inc. P.O. Box 7191 Groton, CT 06340-7191		10. Work Unit No. (TRAIS) 11. Contract or Grant No. C DTRS-97-P-80307
12. Sponsoring Agency Name and Address U.S. Department of Transportation United States Coast Guard Systems, (G-S) Washington, DC 20593-0001	U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, CT 06340-6096	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code Commandant (G-SEN) U.S. Coast Guard Headquarters Washington, DC 20593-0001

15. Supplementary Notes

The R&DC technical point of contact is Dr. Stephen Allen, 860-441-2731.

16. Abstract (Maximum 200 words)

Overview: This report summarizes the results of a 5-year study to ascertain the magnitude of emission problems from Coast Guard and commercial vessels; to develop methodology applicable for use on small vessels by using portable emission analyzers, and to examine various potential means of reducing excessive emissions. During this project, the Coast Guard R&D Center tested eight vessels (of six types); and the Volpe National Transportation Systems Center tested six Coast Guard vessels (of five types) operating on the West Coast. Of the 14 vessels tested, eight were found to exceed the proposed NOx limits, although some by very small amounts.

Basic research at the CG Academy included a multivariate statistical study that showed how NOx can be reduced using diesel/natural gas at lower compression ratios. Another study there showed that most commercial fuel additives are good for cleaning dirty engines to enhance performance, but do not reduce NOx *per se*.

Research at MIT showed that aqueous injection in the exhaust does not materially reduce the gaseous emissions. Another study showed that most of the carcinogenic materials found on the particulate matter are from the consumed lubricating oil.

Research at Penn State on ceramic-coated engine parts showed that although there was no material change in NOx emissions, there was a significant reduction in the condensable (carcinogenic) compounds on the particulates.

Shipboard Test Protocol: Different commercial test instruments were compared with each other and with "standard" methods of analysis, and were shown to be satisfactory for field, or shipboard use. The report includes lessons learned through a wide variety of vessel types ranging from a 41' UTB, to a 600' Navy LSD. Data reduction methods are presented.

17. Key Words gaseous emissions particulates dual fuels ceramic coatings portable instrumentation emission data reduction	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. SECURITY CLASSIF. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

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METRIC CONVERSION FACTORS

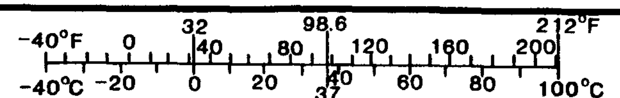
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGMENTS

This project began with a meeting held at Coast Guard Headquarters in 1992. Representatives of the R&D Center, Coast Guard offices of G-MSO (then G-MTH), and G-ENE, the US Maritime Administration, and the US EPA attended it.

Of the attendees at the first meeting, two people deserve special mention. They are Daniel Leubecker from MARAD, and Wayne Lundy of G-MSO. Daniel Leubecker was directly connected with the project from beginning to end. He provided extensive encouragement, and significant funding for the Kings Pointer test, and the final year's research effort at MIT. Wayne Lundy promoted the project at Headquarters, until the scope fell more under the purview of Naval Engineering. At that time Marc Blanchard (G-ENE) acted as co-sponsor, and later took over as Program Manager. His relief was John Hautala who became a significant contributor to the project because of his thorough knowledge of diesel engines, and his great enthusiasm.

At the Coast Guard Academy, Dr. Sharon Zelmanowitz contributed to our initial information database through summer employment at the R&D Center. She then encouraged cadets over a two-year period to conduct independent research projects in line with our objectives of this project. CAPT John Maxham, Head of the Engineering Dept. Was very cooperative in allowing us to use his engine test lab, make modifications to the engines, and make use of enlisted personnel.

Major contributors to the project from the R&D Center were Dr. Stephen Allen, Elizabeth Weaver, James Bellemare, Bert Macesker, and Bob Desruisseau. There were many others who contributed in many ways - consulting, participating in field deployments, etc.

Rodney Cook of the Volpe National Transportation Systems Center contributed by contracting with Environmental Transportation Consultants to test six of Coast Guard vessels. He also served as test director for the KENNEBEC, and contractor for several reports including this one.

At MIT, Dr. Alan Brown (Naval Graduate Program), and Dr. Victor Wong (Sloan Automotive Lab) facilitated working with the Navy and Coast Guard officer graduate students. Of those, R.B. Laurence deserves special mention. He participated in the Point Turner tests.

At Penn State, Dr. Andre' Boehman is to be commended for his enthusiasm, interest, and cooperation. Manohar Vittal deserves special credit in helping set up the engine laboratory.

Much good work was accomplished; much more remains to be done.

Alan P. Bentz
Stonington CT
9 December 1997

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ABBREVIATIONS USED IN THIS WORK

BTU	British thermal units
CARB	California Air Resources Board (Known as ARB in CA)
CFM	Cubic feet per minute
CFR	Cooperative Fuel Research, or Code of Federal Regulations*
CG	Coast Guard
CGA	US Coast Guard Academy
CGC	Coast Guard Cutter
DDEC	Detroit Diesel - Electronically controlled
DFC	Direct Fuel Cell
DOE	Department of Energy
EPA (or US EPA)	Environmental Protection Agency
ERPM (or erpm)	Engine revolutions per minute
ETC	Environmental Transportation Consultants
FID	Flame ionization detector
FTIR	Fourier Transform infrared
FWG	Federal Work Group
g/kWhr	Grams per kilowatt-hour
gal/min (or GPM)	Gallons per minute
gal/hr (or GPH)	Gallons per hour
gal/mi	Gallons per mile
GC	Gas chromatography
GC/MS	Gas chromatography/mass spectrometry
G-ENE	USCG Naval Engineering Division
G-MSO	USCG Hazardous Materials Division (current)
G-MTH	USCG Hazardous Material Transportation Division (Now G-MSO)
HP (or hp)	Horsepower
HPLC	High performance liquid chromatography
IMO	International Maritime Organization
ISO	International Standards Organization
LSD	Landing Ship Dock
MARAD	US Maritime Administration
MCFC	Molten carbonate fuel cells
MIT	Massachusetts Institute of Technology
MLB	Motor lifeboat
MPDE	Main propulsion diesel engine
NAVSSES	Naval Sea Systems Engineering Station
NDIR	Non-dispersive infrared
NMEI	National Maritime Enhancement Institute
NOAA	National Oceanographic and Space Administration

* Depending on context

NPT	National pipe thread
OPEVAL	Operational evaluation
PM	Particulate Matter
PSU	Pennsylvania State University
R&DC (or RDC)	USCG Research and Development Center
RH	Relative humidity
RPM (or rpm)	Revolutions per minute
SCR	Selective catalytic reduction
SEM	Scanning electron microscope
SI	Spark ignition
SOF	Soluble organic fraction
SRPM (or srpm)	Shaft revolutions per minute
Stbd	Starboard
T-AGOS	Acoustic ocean surveillance vessel
T&E	Test and evaluation
TBC	Thermal barrier coating
UHC	Unburned hydrocarbons
USCG	US Coast Guard
USN	US Navy
VNTSC	Volpe National Transportation Systems Center
WLIC	Construction tender - inland
WPB	Patrol boat - medium

EXECUTIVE SUMMARY

Impetus - The Clean Air Act Amendments of 1990. IMO deliberations, the California Air Resources Board, and the Environmental Protection Agency were espousing severe restrictions on marine exhaust emissions. These and other off-road sources contribute to the overall burden of air pollution - the worst components of which are NOx emissions and particulates. The problem was to ascertain current levels of emissions, and then find suitable, economic, and safe means to meet the prescribed levels.

Objective - To adapt portable field testing equipment to measuring emission factors on small vessels, and to use the methodology for determining interactions of engine operating variables to find the means to minimize pollution.

Overview - This report summarizes the results of a 5-year study to ascertain the magnitude of emission problems from Coast Guard and commercial vessels; to develop methodology applicable for use on small vessels by using portable emission analyzers; and to examine various potential means of ameliorating excessive emissions.

Shipboard Tests - During this project, the Coast Guard R&D Center tested eight vessels (of six types); and a contractor tested six Coast Guard vessels (of five types) operating on the West Coast. Of the fourteen vessels tested, eight were found to exceed the proposed NOx limits, although some by very small amounts.

Shipboard Test Protocol - Different commercial portable test instruments, based on electrochemical sensors, were compared with each other and with "standard" methods of analysis, and were shown to be satisfactory for field, or shipboard use. This report includes lessons learned through a wide variety of vessel types ranging from a 41' UTB, to a 600' Navy LSD. Test procedures for a broad spectrum of vessel types are discussed.

Calculations - A rigorous method of calculation of emissions was developed, based on complete material balance of the exhaust emissions with the entering air and fuel. Alternative calculation methods are presented as well.

Research at the CG Academy - This included a multivariate statistical study that showed how NOx can be reduced using diesel/natural gas at lower compression ratios. Another study there showed that most commercial fuel additives are good for cleaning dirty engine to enhance performance, but do not reduce NOx *per se*.

Research at MIT – Aqueous injection in the exhaust was found not to materially reduce the gaseous emissions. Another study showed that most of the carcinogenic materials found on the particulate matter are from the consumed lubricating oil.

Research at Penn State - Ceramic-coated engine parts (thermal barriers) showed that although there was no material change in NOx emissions, there was a significant reduction in the condensable (carcinogenic) compounds on the particulates.

1.0 Background

1.1 Project Evolution

In November 1991, Coast Guard Headquarters Hazardous Material Division (now G-MSO, then G-MTH) requested the U.S. Coast Guard Research and Development Center (USCG R&DC) to prepare a joint U.S. Maritime Administration (MARAD)/USCG project entitled ***Air Pollution Reduction From Marine Engines(Alternative Fuels)***. After meeting with representatives of the Coast Guard, MARAD, and the U.S. Environmental Protection Agency (EPA), the objectives, and technical approach were defined. In December 1992 a formal proposal was submitted to G-MSO, with a copy to the Naval Engineering Branch (G-ENE).

Originally, the work was envisioned as a project to investigate alternative fuels. It was conducted under Project 3301, with G-MTH as the primary sponsor. The scope was later broadened to become the marine diesel exhaust emission project because of a commitment by the Commandant of the Coast Guard with the Director of the US EPA. The project carried the subtitle of "alternate fuels", i.e. alternate fuels being one of many ways to minimize emission pollution.

After FY92, the project fell under Project 3310. The primary sponsorship of this project was formally turned over to G-ENE on 19 October 1994. MARAD contributed half of the total funding from FY92 through FY95, either directly or indirectly. The indirect funding consisted of a National Maritime Educational Institute grant to the Massachusetts Institute of Technology.

1.2 Regulatory Requirements

The impetus for this work was the expected regulations by the California Air Resources Board (CARB), and the U.S. Environmental Protection Agency (EPA). The U.S. Clean Air Act Amendments of 1990, Section (a)(3), charged the EPA with defining and controlling the emission inputs from non-road sources, including marine sources. The U.S. Coast Guard's interest in emissions testing arose not only from its desire to meet all federal and state quality regulations, but the fact that it might be called upon in the future to enforce regulations in the marine environment.

To avoid duplication of effort, the USCG started a Federal Work Group with six agencies, including CARB, EPA, the Department of Energy (DOE), the National Oceanographic and Air Administration (NOAA), and the U.S. Navy (USN). On the international level, the IMO has developed proposed guidelines for controlling air pollution from ships. Additional discussion on regulatory actions, including proposed emission levels, can be found in Reference [1].

2.0 Introduction

2.1 Scope and Objectives

2.1.1 Overview of Technical Approach

The first requirement, before attempting to reduce emissions, was to assess the state-of-the-art, and measure actual emissions. Comparison of the emissions relative to proposed limitations set up by the International Maritime Organization (IMO), CARB, or the EPA would establish the magnitude of the problem. To study the variables affecting emissions, laboratory testing was conducted using a Cooperative Fuel Research (CFR) engine, which provided more controlled conditions than on actual vessels.

The original multi-year technical approach is depicted in the event-flow diagram shown in Figure 1 below:

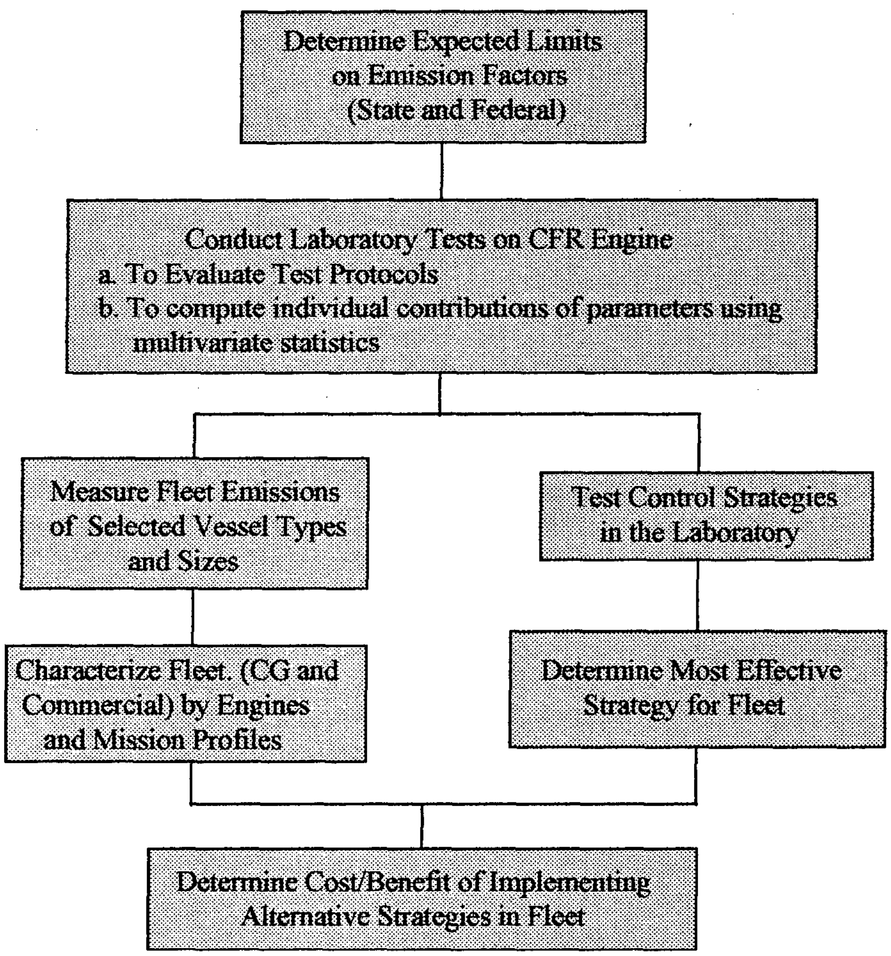


Figure 1. Original Project Plan (4 December 1992)

The general plan was adhered to throughout much of the project, with a few areas expanded, as circumstances or information dictated. The determination of the most effective strategies and the cost/benefit of implementing the strategies in the Fleet remain to be done and are within the purview of the sponsor.

2.1.2 Orientation

Orientation in the project started with an extensive literature search that resulted in a database with about 350 references. It also included: attendance and presentations at the EPA Public Workshop on Marine Engines and Vessels, held in Ann Arbor MI in July 1992; and the biennial DOE-sponsored Diesel Engine Emissions Reduction Workshops held in La Jolla CA (University of San Diego) in 1993 and 1995. Other meetings included: Society of Automotive Engineers, Marine Session, Milwaukee WI, 1994; American Society of Mechanical Engineers (internal Combustion Engine Div.) in Milwaukee 1995; *Marine Log*-sponsored meetings of Propulsion 95 and 96 in New Orleans.

The Federal Work Group (FWG) met approximately every six months, and included presentations of all work done by member agencies. In addition, one Coast Guard member of the FWG also attended the IMO meetings in London. One meeting was held in Washington of the Subcommittee on Bulk Chemicals of IMO, and was attended by R&DC personnel. The meeting was largely comprised of shippers and engine manufacturers. However, Dr. G.L. Reynolds, Head of Lloyd's Register Environmental Engineering Section, which was currently conducting the most extensive shipboard testing under their "Marine Exhaust Emissions Research Programme", also attended it.

Instrument manufacturers were surveyed for the latest instrumentation applicable to field analysis. Ultimately, three commercially available instrument types were purchased for portable exhaust emission testing - all based on the same type of electrochemical detector.

2.2 Technical Approach

The technical approach outlined in Figure 1 evolved into overlapping, and some concurrent in-house laboratory studies, shipboard tests, and outside academic laboratory studies as described below.

2.2.1 In-House Laboratory Studies

In-house laboratory work was conducted at the U.S. Coast Guard Academy (USCGA) in the Engine Laboratory in the Mechanical Engineering Department. For this purpose a CFR engine was used to study the interaction of variables (temperature, compression ratio, airflow, etc.), as well as dual fuel (diesel/natural gas). Another study was conducted to test the efficacy of fuel additives.

The CFR engine is a single-cylinder engine, which may not accurately reflect the situation on full-scale turbocharged engines. It was therefore necessary to test actual vessels.

2.2.2 Shipboard Testing

Because of concern that laboratory bench testing does not duplicate the actual in-service load cycles on marine engines, and that performance of in-service engines degrades in time and their emissions increase, it was decided to measure emissions at-sea to test real-world emissions.

The International Standards Organization Work Group SC8 on Exhaust Emissions Measurement published a tentative standard ISO 8178 (Reference [3a]) listing several duty cycles. The US EPA recommends cycle E3 for heavy-duty marine engines. This test is conducted at four prescribed power or speed settings (measuring emissions as a percentage of full speed, and reporting as a weighted average of the four values). There may be several modes of operation for real vessels (duty cycles) with defined speed, power, and time. Since we were interested in the actual emissions from a vessel in operation (as opposed to emissions from its engine on a laboratory test block), we varied the prescribed settings in some instances to better reflect the actual vessel duty cycle.

The scope of shipboard testing was to encompass as large a variety of vessels to encounter as many types of problems as possible to be able to address them in a generic protocol applicable to any vessel. The range went from a 47' motor lifeboat to a 600' Navy Landing Ship Dock (LSD). With the exception of one diesel-electric powered ship, all tests were conducted on diesel propulsion systems.

2.2.3 Academic Testing - Massachusetts Institute of Technology (MIT)

Tests related to this project were conducted under the Navy Graduate Program in the Ocean Engineering Department of MIT. The work was done by Navy and Coast Guard officers as graduate students who obtained a dual Master's Degree in ocean engineering and mechanical engineering.

The first thesis [4] involved an engine modification to model the wet exhaust found on the USCG 82' Patrol Boats (WPBs). The purpose was to find out whether a significant percentage of the exhaust products went into the water column rather than the air, since the exhaust gases are mostly water-soluble acid anhydrides. This was important to know since the concern of this project was under the Clean Air Act Amendments of 1990 (See Section 1.2, page 1).

The Consortium on Lubrication in Internal Combustion Engines funded the bulk of the MIT work conducted in the Sloan Automotive Laboratory. This put emphasis on lubricating oils, piston rings, and the variables relating thereto. However, the experimental design included the variables of interest to the Coast Guard. Also, lubrication studies helped answer the question of how much of the combustion products in the exhaust came from lubricating oil, rather than fuel oil. This is

important, since most researchers are concerned with the cleanliness of the marine diesel fuel (especially sulfur) without regard to the impact of significant oil consumption.

An additional aspect of the work in the MIT laboratory was determination of particulate emissions as a function of engine operating parameters. Even beyond determination of particulates *per se*, we investigated the soluble organic fraction (SOF) in the oily carbonaceous residues as a function of operating conditions.

2.2.4 Academic Testing - Pennsylvania State University (PSU)

The Fuel Science Laboratory at PSU is in the Department of Material Science, and for this reason provides the engine laboratory access to some very sophisticated analytical techniques, including: gas chromatography/mass spectrometry (GC/MS), Fourier Transform infrared spectroscopy (FTIR), nuclear magnetic resonance (nmr), as well as the only university-owned Micro Dilution Tunnel for particulate analysis.

2.3 Other Avenues Explored

There are numerous emission reduction techniques available, involving engine operating parameters, diesel fuel composition and alternate fuels. The operating premise was that DOE was pressing for "Year 2000 Engines" to meet the EPA/IMO criteria for emissions.

Some of the exhaust treatment systems were exorbitantly expensive and occupied about as much space as the power plants themselves. These were not readily installed by retrofitting; ideally they would be incorporated into new ship design. Military vessels (USN and USCG) are designed for specific missions, and do not have extra space for such systems without sacrificing something like a helicopter pad - which would severely restrict the mission capability.

2.3.1 Dual Fuel (Diesel/Natural Gas)

Alternate fuels, and fuel additives are for the most part being examined by the engine manufacturers. Use of oxygenated fuels opens up new engine requirements, and raised the question of the long-term effects of their combustion products (e.g. formaldehyde and acetaldehyde). In this project, we did examine up to 80% natural gas in diesel fuel, and demonstrated some benefit under proper conditions.

2.3.2 Fuel Additives

As mentioned in Section 2.2.1, a small study was conducted on common fuel additives to assess their beneficial effects on emissions. It was not pursued further, because DOE is funding a large effort through Texaco and the University of Wisconsin. Their additive is cyanuric acid, which chemically alters the combustion to minimize the formation of nitrogen oxides (NOx). This compound is unlike existing commercial additives that are based mainly on surfactants and dispersants that function in effect by cleaning the engine.

Cyanuric acid is theoretically an ideal compound to use. However, it is a solid at room temperature, and is not directly soluble in diesel fuel. Initially, its use involved modifying the engine to inject the molten material at a precise time during the combustion. The present approach is to encapsulate, and suspend it in the fuel in such a way as to have it released at the appropriate time during the combustion.

2.3.3 Ceramic Coatings

We examined the influence of simple ceramic coatings of the piston head, cylinder head and valves tips in a cooperative effort with Penn State.

2.3.4 Fuel Cells

A new advance in molten fuel cell design made it expedient to examine the use of fuel cells as an alternative to internal combustion of the diesel fuel. Extensive examination of the concept made it appear the propitious time to test the feasibility on a full-sized vessel. The ideal candidate was a T-AGOS (similar to the *KINGS POINTER*) which has diesel-electric propulsion.

2.3.5 Turbodyne

One of the attributes of cold startup of diesel engines is the noxious, smoky exhaust - particularly on the Island Class cutters (110' WPBs). It lasts for several minutes while the engine warms up.

The Turbodyne Corporation reported a device, which although not especially designed for cold startup, reduces "turbo lag" by spinning up the turbocharger impeller during transient conditions. It is highly successful during "snap acceleration" in truck engines. However, it was not designed to operate continuously because of the power requirements. Marine diesels generally operate at steady state, and are not subjected to the "snap acceleration" repeatedly encountered with trucks. It was dropped from consideration for the 110' WPBs, because the device was not designed to operate at startup and run continuously while the engine idles.

3.0 Test Requirements

On the surface, the test measurements would appear to be quite straightforward. A material balance is conducted by measuring the incoming fuel and air and comparing it with the total exhaust. The technical difficulties are varied, and complicated by the fact that the air temperature and humidity must be accurately measured, in addition to the flow rate.

3.1 Overview of Test Data and Equipment

3.1.1 Data Collected

In order to relate measured emissions data to ship operating characteristics, a number of physical variables had to be measured. A complete discussion of the variables that affect engine exhaust emissions may be found in Reference [5]. Data listed in Table 1 (next page) were collected. Below is a discussion of how each variable was measured. The technique used was that normally applied to typical vessels tested. Exceptions are noted.

Table 1
Ship Test Data Collected

Barometric Pressure (inches of Hg)	Intake Air Flow (CFM)
Relative humidity near engine intake (%)	Stack Temperature (°F)
Temperature associated with relative humidity (°F)	Oxygen volume (dry) in exhaust (%)
Intake Air Temperature (°F)	CO volume (dry) in exhaust (%)
Shaft rpm (port & stbd)	Excess Air Volume (dry) in exh (%)
Engine rpm (port & stbd)	NO volume (dry) in exhaust (ppm)
Shaft Horsepower	NO_2 volume (dry) in exhaust (ppm)
Fuel Flow (GPH)	NOx volume (dry) in exhaust (ppm)

3.1.2 Air Measurements

Air measurements necessary for the material balance include the airflow rate, barometric pressure, relative humidity, and air temperature. Shortridge Flowhoods™ [6] [a] were attached to the turbocharger, and provided air pressure and temperature, as well as flow rate in cubic feet per minute (CFM). For larger engines with two turbochargers, a Flowhood was installed on each inboard turbocharger, and the total air intake was obtained by doubling the reading taken.

The diameter of the air intakes varied from 7" on the 47' motor lifeboats to 36" on the Navy Landing Ship Dock (LSD), requiring differing measurement techniques. A 36" differential pitot, tube equipped with a calibrated digital readout was used on the LSD.

The Control Data Digital Recorder was used for relative humidity, air temperature, and barometric pressure. It was checked prior to use against the University of Connecticut's Marine Science Institute equipment. Readings agreed within 4%. Relative humidity readings were also checked against a Dickson Company Model THDx humidity sensor while in the engine room.. All of these data were also recorded manually.

[a] Use of trade names does not constitute an endorsement by the U.S. Coast Guard

Barometric pressure was recorded in the engine room on the Control Data Digital Recorder. Barometric pressure and intake air temperature was also recorded by each of two Shortridge Flowhoods. Generally each was installed on a different engine. Temperature readings were confirmed against temperature readings available on the Control Data Digital Recorder and THDx chart recorder.

3.1.3 Shaft rpm/Engine rpm

Shaft rpm (SRPM), or engine rpm (ERPM) are required measurements. The relation between these is determined by the gear reduction between the engine and the propeller shaft. This information is necessary to compute the power output, and for calculation of pollutants per unit of power (horsepower or kilowatt-hours).

3.1.4 Shaft Horsepower/Torque

Shaft rpm and shaft horsepower (SHP) were measured with Coast Guard-owned horsepower (HP) meters [7]. Shaft torque was measured on the port and starboard shafts with strain gauges during each test run to determine shaft HP. Each propulsion shaft was outfitted with a Wireless Data Corporation Model 1642A horsepower measuring system [6], which consisted of a strain gauge, bonded to the outside of the shaft and a magnetic pickup that recorded the rpm. An FM transmitter collar system transmitted the strain information to the horsepower meter. The measured strain was converted to torque, and the HP calculated.

This approach for measuring shaft horsepower has been the approach the R&D Center has employed for the last two decades when instrumenting various Coast Guard vessels for test & evaluation (T&E). This has proven to be a reliable and consistent approach over the years. It is, however, a time consuming and demanding procedure that requires a skilled technician. Meticulous care is taken to prepare the shaft for strain gauges as well as the system setup. This process can take from 12 to 24 hours depending on accessibility of the shafts.

Engine rpm (ERPM) and horsepower (HP) were also measured by the Stellar Marine fuel management system (EMS-1000). This alternative means of determining *in-situ* horsepower of main diesel engines is based on the fuel rack positions. The premise behind the EMS-1000 in Reference [8] is that diesel engines are equipped with precise fuel metering systems in that the fuel injectors deliver a precise amount of fuel into each cylinder at specific intervals. The quantity and rate of fuel is determined by the settings on the engine rpm and fuel racks. The EMS-1000 measures fuel consumption using the engines own fuel metering system. The EMS-1000 Main Control Unit uses a patented algorithm to determine fuel rate and horsepower based on the fuel rack position, rpm, and engine manufacturer's test data. Engine rpm is determined with a magnetic pickup that senses and counts the number of flywheel teeth that pass by its position. The data were recorded manually and also recorded continuously by the Stellar Marine EMS-1000 data-logging software. The reduction gear ratio was accurately determined by comparing SRPM and ERPM. The unit has a GPS system to measure speed and direction.

The EMS-1000 was compared with the Wireless Data equipment in extensive studies in ferries and barges on the West Coast, and found equivalent. In fact, it had one advantage over the Wireless Data measurement: it was not subject to effects of temperature on the propeller shaft [9]. The Volpe National Transportation Systems Center (NVTSC) and its contractor Environmental Transportation Consultants used the EMS-1000 exclusively in all tests of six CG vessels.

3.1.5 Fuel Consumption

On the early tests, spring-loaded flowmeters were installed in the fuel inlet and return lines, and the difference represented the net flow into the cylinders. For the LSD and the Kings Pointer, the Navy provided accurately calibrated flowmeters. The cost was about $10K, not including travel and per diem for two individuals for one week.

The Stellar Marine fuel management system (EMS-1000) was used to measure fuel consumption, speed, and HP. Fuel consumption was determined with a potentiometer that recorded the fuel rack position calibrated to fuel used.

The Stellar Marine engine speed pilot (ESP-1000) was also installed and required tapping into the throttle pneumatic system. It uses proprietary software to adjust throttle settings to accomplish two things: first, it balances the two engines which saves 1-3% in energy; second, it optimizes the engine speed to get the most power with the lowest rpm. ESP-1000 is analogous to an automobile cruise control. Both the EMS-1000 and ESP-1000 software were installed on the Gateway 2000 laptop. The laptop was used to engage and disengage the engine speed pilot.

3.1.6 Exhaust Gases

Emission analyzers that employ electrochemical sensors recorded the composition of exhaust gases in ppm or percent concentrations. A probe was inserted through a fitting on the exhaust stack located less about two feet above the engine. Exhaust gas concentrations of CO, NO, NO_2, SO_2, O_2 were recorded manually by Coast Guard personnel, and the data were streamed to the EMS-1000 for continuous data logging. In the first tests aboard the Point Class cutters, the Lanscom 6500 was also used. Later, two different analyzers were used including the ENERAC Model 3000E, and ECOM-KD. The sensor's accuracy for NO, NO_2, and CO ppm readings on the ECOM-KD [11] and ENERAC 3000E [12] are advertised as 5% and 2%, respectively.

3.2 Portable Test Instrumentation Discussion

Standard emission testing used chemiluminescence, gas chromatography and infrared [13] which are bulky, and require a fork lift truck to move them, and a crane to place them on a vessel. For that reason, we opted for the electrochemical sensors that were commercially packaged in a briefcase-sized case, and measured CO, NO, NO_2, unburned hydrocarbons, and computed CO_2, NOx, and excess oxygen.

3.2.1 Final Instrumentation Configuration Used.

After conducting numerous shipboard tests, a test setup evolved in which the instruments were all connected to the same data logger. The last test was conducted on the construction tender *KENNEBEC* (WLIC-160). Figure 2 provides a schematic overview of the instrumentation used on the *KENNEBEC*.

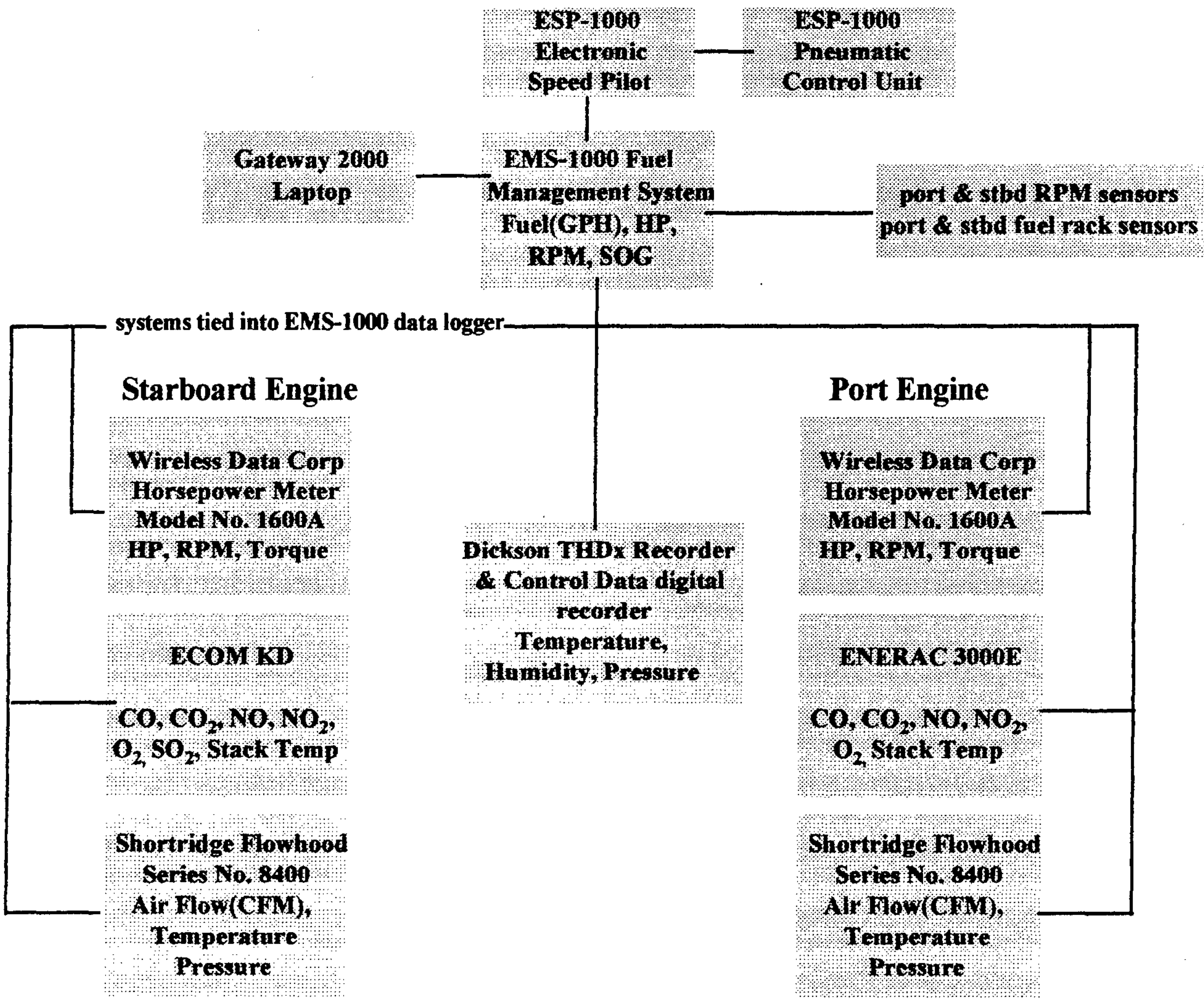


Figure 2. Overview of Construction Tender KENNEBEC Instrumentation

The instrumentation used on the KENNEBEC was based on all our previous experience. We used two different analyzers and two different power meters to get comparison on their ease of use, and reliability - as well as independent checks on the results.

Without exception, including the KENNEBEC, the real-world shipboard tests were replete with problems and unforeseen difficulties. The purpose of testing multiple vessel types was to encounter as many of these problems as possible in order to generate the best generic shipboard

test with the broadest range of applications, and be able to suggest means to overcome the types of difficulties that were met.

3.2.2 Traditionally-Used Instrumentation

The recommended method for sampling and measuring emissions is that given in the US Code of Federal Regulations [13], and the US Federal Register [14]. These are obviously not designed for shipboard field operation. Lloyd's Register personnel employed a gas chromatograph (GC) with flame ionization detector (FID) for analyzing unburned hydrocarbons; non-dispersive infrared (NDIR) for NO/SO_2, and another NDIR for CO/CO_2, and a paramagnetic oxygen analyzer. The equipment fits on a large pallet, requiring a fork lift truck for "portability." It also requires carrier gas and hydrogen cylinders for the GC.

Similarly, MIT uses a "gas cart" six feet wide, six feet high and 3 feet deep. It is on wheels, so can be moved in a laboratory environment. The gas cart also required an accompanying cart about the same size to carry the necessary gas cylinders. The cart has two Beckman Model 865 infrared instruments to measure CO and CO_2. It also has a Beckman Model OM-11 EA oxygen analyzer which employs a polarographic technique (dropping mercury electrode). Finally, a chemiluminescence instrument is used to measure NO and NOx.

These methods are well tested, and reliable. They are not too difficult to use on large ships with the help of cranes. The are too large to use on small boats like the 42', and 47', or even the 82' Coast Guard vessels.

3.2.3 Electrochemical Instruments

There are a number of commercially available emission analyzers that are truly portable. They are based on electrochemical sensors made in Germany, and all are approximately the size of a large briefcase. They can measure, and or compute the NO, NO_2, NOx, CO, CO_2, SO_2, unburned hydrocarbons, and residual oxygen.

They were originally designed to test stack gases from industrial plants. They did not have some of the restricted space, high operating temperatures and movable platform problems of shipboard testing. As pointed out in Section 3.1.6, we had started with the Lanscom 6500. Originally, it was necessary to press a button to start the analysis, and wait for the paper tape to print out the results. It was tedious, because of all the other readings such as airflow, air temperature, air pressure, humidity, etc. That had to be obtained simultaneously. Furthermore, it did not permit measurements of transients on acceleration, or deceleration.

Later versions came out with computer interfacing capabilities for continuous recording, or data acquisition at specified intervals - thus releasing the operator for other duties in data collection..

To test the equivalence of the portable (electrochemical) instruments to the standard accepted methods, an ENERAC 2000E was loaned to MIT, and all measurements were done on the gas

cart and the ENERAC. There was a slight disparity, and it was found that the ENERAC was stable and pointed to a small leak in the gas cart lines.

ENERAC Model 3000E is purported to give more reliable NOx readings, based on its design incorporating a thermal control to eliminate cross contamination, provide multiple sensor ranges, and absorption losses. (It was approved by the US EPA for their Conditional Test Method CT-022 [15]). This, and the ECOM KD were the latest instruments used. They were directly compared on the CGC KENNEBEC.

Calibrations of both instruments were conducted the day before the KENNEBEC tests (11 November) with factory representatives of each company present. They were calibrated before the test, in accordance with their respective manuals [11] and [12]. The span gas readings were checked about 1/3 of the way into the test. The ECOM results are shown in parentheses; the ENERAC was apparently off, and was recalibrated. After the shipboard test (final test P98), the two instruments were rechecked to estimate their drift, with the following results:

Table 2 - Instrument Readings at End of Test
(originally calibrated to nominal span gas values)

Gas	Span Gas (ppm)	ECOM-KD[a] Rdg (ppm)	Span Gas (ppm)	ENERAC 3000E[b] Rdg (ppm)
CO	500	545 (505)	500	494
NO	100	103 (101)	100	86
NO_2	100	112 (99)	100	98
SO_2	100	113 (98)	100	99

[a] The ECOM readings are shown in parenthesis at 1/3 point; calibration left as is.
[b] The ENERAC was recalibrated at 1/3 point (readings there not available).

The most serious drift appears to be that of the ENERAC 3000E for the NO readings, where it dropped 14%. This is doubly puzzling, since the ECOM-KD drifted ***up*** 3%. Since the detectors are essentially the same, this is anomalous behavior that hasn't been explained. The ECOM drifted up 12 and 13% for NO_2 and SO_2, while the ENERAC stayed within 1-2%. The ECOM drifted up 9% for CO, while the ENERAC stayed within about 1%.

These data are reported here to demonstrate that, despite considerable experience with the equipment, despite having factory representatives there for initial calibration, some inexplicable results can still be obtained. Since the ENERAC-3000 is sufficiently accurate to have been accepted for the EPA's Conditional Test Method (CT-022) for NOx measurement [15], it is not suggested that the observed drift is the fault of the instrument. However, it did exhibit significant drift aboard the commercial tug COUGAR (see TABLE 13, p 36, and accompanying discussion).

3.2.4 Power Meters

Both a strain gauge-based power meter, and a fuel consumption-based unit were used in hope of getting a direct comparison, and to determine whether the strain-gauge measurements, which are very labor intensive, were really necessary in a streamlined emissions protocol. These comparisons have been made in the past with very good agreement on barges and ferries on the West Coast [8]. In fact, the Stellar Marine EMS-1000 is not subject to temperature variations that are noticeable with the strain gauge when the shaft heats up [9](see discussion in 3.1.4, p 8).

3.2.5 Fuel Flow

Obviously, fuel savings are of great interest to both industry and the Coast Guard. The Stellar Marine EMS-1000 measures the fuel flow very accurately. Stellar Marine engine speed pilot (ESP-1000) uses proprietary software to adjust throttle settings to accomplish two things: first, it balances the two engines which saves 1-3% in energy; second, it optimizes the engine speed to get the most power with the lowest rpm. At equilibrium conditions, this translates into lower fuel consumption.

For the KENNEBEC, both the EMS-1000 and ESP-1000 software were installed on the Gateway 2000 laptop. The laptop was used to engage and disengage the engine speed pilot. The evaluation of the ESP-1000 was to be accomplished on a not-to-interfere basis with the primary emission data collection. The results under the test conditions were not definitive, but were encouraging enough to warrant further testing.

3.2.6 Sampling for Emission Measurements

Fittings are installed in the port and starboard exhaust stacks about a foot above the engine to accommodate ball valves. The ball valves were opened after steady-state stack temperatures were attained at which point the emission analyzer probes were inserted. The Shortridge Flowhoods were attached to the inboard port and starboard turbochargers if dual, otherwise one to each turbocharger.

3.3 Experimental Design

The experimental design used for testing shipboard engines is based on the test modes and weighting factors recommended by ISO 8178 Part 4 [3a]. The method, however, is designed for engines in a laboratory on a test bed with a dynamometer attached. The ISO test specifies that inlet restriction and exhaust backpressure shall be adjusted to the manufacturer's upper limits.

In the shipboard situation, we do not have a dynamometer attached, and do not want to alter the normal operation of the ship's engine by modifying the back pressure, i.e. we want to measure the actual emissions of the vessel during its normal operating profile.

The ISO mode E3 is specified for heavy-duty marine engines, and is the method of choice for the larger vessels. It is outlined in Table 3 below as specified in ISO 8178.

Table 3 - ISO 8178 Mode E3 for Heavy-Duty Marine Engines

	1	2	3	4
Power % (ISO)	100	75	50	25
Speed % (ISO)	100	91	80	63
Weighting Factor	0.2	0.5	0.15	0.15

The first three vessels tested were 82' WPBs, the ship operating profiles were far different from large vessels that maneuver in docking and undocking, but spend most of their time at a cruising speed. These skippers of these vessels were polled, and the picture of the profile emerged. On search and rescue missions, they traveled at full speed to the site, but used idle and clutch speeds very much for both rescue and boarding operations.

We decided to adapt ISO 8178 Cycle E-4 for "pleasure craft spark ignited and Diesel - engines especially designed for marine application, which added a fifth speed, namely idle. It was for craft less than 24 m (78.92 ft) in length. Although the 82' WPBs were slightly longer, this matrix was applied to them as shown in Table 4.

Table 4 - ISO 8178 Mode E4
(Based on Vessel Duty Cycle)

	1	2	3	4	5
Speed, ISO (%)	100	80	60	40	idle
Torque, ISO (%)	100	71.6	46.5	25.3	0
Weighting Factor	0.06	0.14	0.15	0.25	0.40

Subsequent to the 82' WPB tests, an ISO mode number cycle E5 was promulgated [16], which used the same speed and power percentages as E3, but included the idle. The weighting factors were: 0.08, 0.13, 0.17, 0.32 and 0.3 for speeds of 100%, 91%, 80%, 63%, and idle, respectively. [Note: these weighting factors are far different from the actual operating profiles of the 82-footers].

In order to achieve the settings, it was experimentally necessary to use the engine and/or shaft speed, and measure the power obtained. This was rarely near the power, or torque specified by the ISO, since it depended upon load, which in turn depended on the vessel loading, the sea state, currents, and wind direction. It also depends on whether there is acceleration, deceleration, or a steady state situation where the momentum is just maintained. The deviation was especially notable for low speeds as seen below in Table 5.

Table 5 shows the ISO-specified values, and those actually obtained for the USCGC KENNEBEC in the ISO design portion of the testing. To augment those results, emissions were measured at three other speeds that better reflected the vessels operating profile.

Table 5 - Test Speeds used for KENNEBEC (WLIC-160)

	1	**2**	**3**	**4**
Power % (ISO)	100	75	50	25
(Actual)	100[a]	73	42	13
Speed % (ISO)	100	91	80	63
KENNEBEC ERPM Settings	1250 (1237 actual)	1137	1000	790
Weighting Factor	0.2	0.5	0.15	0.15

[a] Percent of actually obtained maximum horsepower from port engine (493 hp at 1237 rpm)

It is seen that the power at the lowest speed was about half the expected (13% vice 25%), and the given rpm. The weighting factors shown were used to calculate a single number for the emission factor.

In the case of the KENNEBEC, three other test points were used, based on the vessels duty cycles seen In Table 6.

In the case of the KENNEBEC, three other test points were used, based on the vessels duty cycles seen In Table 6.

Table 6- Other Speeds Used in KENNEBEC Test (Based on Vessel Duty Cycle)

	5	6	7
Power % (Actual)	97	56	29
Speed %	98	87	74
KENNEBEC ERPM Settings	1225	1090	925

Each speed was replicated four times with the Speed Pilot off, and then another four times with the speed pilot on. Sequences of the four replicates were randomized for all speeds.

The experimental designs were similar for all other vessels, and are given in the Test Plan portion of their respective reports: Refs. [5], [17], [18], [19], [20], [21], [22], [23], [8].

4.0 Vessels Tested, Field Observations, and Lessons Learned.

A variety of vessel types was selected to learn the challenges posed by each. The recently reported studies by Lloyd's Register were conducted on large vessels with slow and medium-speed engines. The attempt here was to try smaller vessels, most with high-speed engines to assess the portable test equipment. Coast Guard vessels were selected in most instances for two reasons: a. the knowledge of their emissions was of importance to measure compliance with proposed emission standards, and to learn the magnitude of any problems if they did not comply; b. CG vessels were more readily accessible to R&D Center personnel, and testing did not interfere with commercial missions.

4.1 Point Class Medium Patrol Boats (WPBs) [5], [17]

4.1.1 General Background

The CG R&D Center first conducted a series of tests involving three Point Class 82-ft patrol boats using these techniques. They were the POINT FRANCIS (New London CT), POINT BROWER (San Francisco CA), and POINT TURNER (Newport RI). The first boat tested was the POINT FRANCIS stationed in New London. It was selected for convenience as a "trial horse," so that it would not be necessary to go back and forth across the country when problems arose. The

Multiple boats were chosen in an effort to get a measure of inter-boat variability. The class originally came equipped with Cummins diesels, which were changed out with Caterpillar D3412 engines of 750-800 hp each. Originally it was planned to test two boats with new Caterpillar engines to get a measure of inter-boat reproducibility, and to test a boat with an old Cummins to see how bad it might have become relative to new engines. However, by the time the first two were tested, the third had already had its new engine installed.

The passageways in the engine room were very narrow, and could not have accommodated anything but our portable equipment. We decided not to test the particulates because the only commercially available test equipment - the Sierra BG-1 Micro Dilution Test Stand - weighs 600 pounds and would not fit in the engine room. Note that it was not used on the 41' UTB by NVTSC/ETC [10, p 8-6] for the same reason.

The calculations of emission factors in g/kWh, are based on full material balance in much the same way that is used in power plant stack emissions [24], with some simplifying assumptions.

4.1.2 Air Measurements

The D3412s were turbocharged engines with a large air intake filter. The two East Coast boats had a circular filter for which a metal adapter was fabricated, and a 10" diameter flexible hose was attached from the filter to the Flowhoods, which were suspended from the overhead. Between the two Flowhoods were placed a recording thermometer, and a hygrometer to obtain the temperature and relative humidity of the entering air. When the equipment was sent to San Francisco for the POINT BROWER, we found that it had rectangular air filters, and required on-the-spot improvisation to measure the air intake.

4.1.3 Power Meters

Installation of the power meters required gaining access to the propeller shaft, cleaning the surface of the shaft and cementing the strain gauges onto the shaft with epoxy resin. There had to be clearance for the radio collar. One vessel, because of the engine changeouts, had a steel bracket in the way that had to be ground out in order to place the radio collar in position. One shaft had a sufficient bend that it kept coming into contact with the collar, ultimately resulting in our being able to measure only the torque of one engine. In another instance the power meter failed during the tests, and left a single readout. This precluded measurement of inter-engine variability, but was not too serious on in the overall calculations, since we were comparing identical new engines of the same displacement operated at the same speeds. The boats each already had a meter that read out rpm enabling a direct comparison with the power meter.

4.1.4 Fuel Consumption

For these boats, accurate fuel consumption was not satisfactorily obtained. In-line flowmeters were attempted on two boats, but they lacked the proper flow range, and created a backpressure

that interfered with the flow. A new meter could not be obtained in time for the third test, so the ship's fuel consumption curve as a function of rpm was employed to estimate the fuel consumption.

4.1.5 Emission Measurements

Sampling the exhaust posed somewhat of a problem. The Lloyd's Register tests [2] involved inserting a probe about a meter down in the exhaust stack of a vessel. The 82' WPBs have a wet exhaust in which there is an aqueous injection downstream for cooling purposes, and the exhaust exits the transom. The aqueous injection raised the question of whether a significant amount of the exhaust gases entered the water and were thereby removed from the air emissions. This question was addressed by Laurence [4] in his MIT thesis.

The electrochemical sensors in the test instruments cannot tolerate water. In fact the exhaust stream is dried to remove water vapor from the air and from combustion in order to get the chemical analysis on a dry basis. It was therefore necessary to obtain a sample directly from the exhaust line upstream of the water injection. Ideally, a sample should be taken after a straight run of about 4'. However, this was not possible. The new exhaust lines coming out of the supercharger each had a sharp bend, and then went aft fully insulated, and inaccessible. It was therefore necessary to install the globe valves for exhaust sampling at the only access port available on the elbow where there was a highly turbulent stream. Probes were inserted only for the duration of the test at each speed (about 5 minutes).

The calculations were basically the same as those shown in Appendix A for the KENNEBEC.

4.2 47-Foot Motor Lifeboat (MLB) [18], [19]

4.2.1 General Background

The technique was applied to a 47-ft motor lifeboat boat (MLB), CG-47201 (Cape May NJ) - the smallest vessel tested by the R&D Center.

In the early acquisition stages of the 47' MLB, one prototype and five preconstruction boats were built. Engine failures occurred before 1200 hours (compared to 5-6000 expected). The R&D Center was tasked to conduct a Technical Evaluation (TECHEVAL) of the DDEC modification on the 6V-92 engines. This was carried out in November 1992, and the final report by LCDR Robert Latas was issued in January 1995 [18], and the report on the concurrent emissions tests appeared in June 1996 [19].

There was extremely short notice of the test, but it was viewed as an opportunity to test our methodology, and find out problems associated with small boat testing. The immediacy of the testing was because of the engine problems. The boat is designed to be able to roll 360° in the water. This is made possible by a watertight seal on the door to the engine room. There was speculation that with this door sealed, there was an inadequate air supply to the engine. The tests

were to be conducted in calm water with the door opened and closed. If the engines were getting an inadequate air supply, it should have been reflected in a higher carbon monoxide to carbon dioxide (CO/CO_2) ratio - which was not observed in the results.

4.2.2 Air Measurements

The air filters were removed, and a 7 1/2" duct attached to the air intake, and adapted to our Flowhoods.

Air is drawn through louvers aft of the engine room on the main deck. A Tygon hose was installed through the louver, and hooked to a manometer to measure the difference of air pressure between the open air, and inside the engine room.

4.2.3 Power Meters

The torque and shaft rpm readings were measured using the Wireless Data Corp. Horsepower Meter, Model 1642 A, located in the survivor compartment. It obtained data from a strain gauge mounted on the propeller shaft underneath. This installation was already made for the TECHEVAL

4.2.4 Fuel Consumption

This boat offered a challenge in measuring fuel flow. The method used was a direct reading one, in which fuel was measured by installing a 1000 mL graduated cylinder in line with the port engine, and the consumption rate noted using a stop watch for the time intervals. The rate was determined by measuring the time (t) in seconds for fuel in milliliters (mL) to be consumed by taking both suction and return from the graduated cylinder and using the relationship shown in Equation (1)

Equation (1) Fuel Consumption (gal/hr) = mL/t x 0.951*
* Based on conversion factor of 0.26418 gal/L

The value thus obtained was multiplied by two to compute the total consumption by both engines.

4.2.5 Emission Measurements

The so-called "calm water" testing was not to be in early November. We encountered 7-8' seas that at times reached 10' in height. On a 47' boat, it was like being on a roller coaster. The emission-testing instrument was buckled onto a seat on the upper deck, and covered with plastic to keep the heavy spray off of the instrument. Needless to say, the instrument was never designed to be used under the pounding conditions encountered, but it performed flawlessly.

The exhaust sampling probe was inserted through a port (1/4" NPT fitting) available for backpressure measurements. It was only a 1/4" opening, so that the usual globe valve could not

be installed. It was therefore necessary to insert a 1/4" plug each time that the probe was removed to avoid having exhaust gases going directly into the engine room. This was not a problem, except for frequent handling of the hot plug each time the exchange was made. The line from the probe was run through the air intake grill, to the instrument on the upper deck.

The calculations of the emission factors by material balance were as applicable to the two-cycle Detroit Diesel engines as they had been for all the four-cycle engines tested. Because of logistic problems, a number of instrumental problems and adverse conditions, only one reliable set of data was obtained. It consisted of tests in triplicate with the engine room door open and closed. Luckily they were all at the rated speed of 2100 rpm (all on 11/12/94). The California Air Resources Board (CARB), and U.S. EPA accept emissions measured at the rated speed.

4.3 USS ASHLAND - Landing Ship Dock (LSD-48) [20]

4.3.1 General Background

In February 1995, the technique was applied to the other extreme in size - a 600-foot Navy Landing Ship Dock (LSD-48, the USS Ashland). (Reference [20]). The USS ASHLAND was selected as an example of a large vessel to test our methodology. Tests were conducted from 14-16 February 1995 in conjunction with sea trials following a private contract repair. The seas were heavy in the Atlantic, and the emission tests were conducted from midnight to 0800 to avoid conflicting with the sea trial testing. The Naval Engineering Graduate Office at MIT was involved in the arrangements, and the results are reported in a thesis by LT Agnes M. Mayeaux as partial fulfillment of the requirements for degrees of Naval Engineer and Master of Science in Mechanical Engineering.

We had equipment for only 2 of the four engines, and selected MPDE 1A, and MPDE 1B.

4.3.2 Air Measurements

Measuring airflow posed one of the biggest problems. The air intake plenums (ducts) were 3 feet in diameter, and the flow was much too large for our Flowhoods. We settled on differential pitot tubes that went across the plenums, and had evenly-spaced holes to take a representative sampling of the cross-section, known as averaging pitot tubes - (ACCUTUBE Model No. 33T). It was a major job to drill the holes for the mounting ports, since the drill filings had to be collected so as not to go into the engine. Luckily the ship was at the Norfolk Yard, and this could be accomplished during the overhaul. To access the intake lines, it was necessary to remove a bolted manhole cover and climb into a dark, 2-story space where the installation took place.

The principle was to measure differential pressure across the tube with a transducer in the uptake room. The transducer transmitted an electrical signal (4-20 ma) which correlated in a linear fashion to the differential pressure. Inadvertently, one of the two pitot tube electrical connections had its polarity reversed, and the response was not the "mirror image" of the reverse polarity, so the values were valid for only one engine intake.

The air pressure measurements were obtained from a vacuum sensor was used since there is an approximately 4" of water pressure drop across even clean air filters. This transducer (Omega Model PX141) permitted calculation of the air density based on the measured air pressure and temperature in the vicinity of the pitot tube. Temperatures were measured with a Chromega-Constantan ungrounded thermocouple.

4.3.3 Power Meters

Engine rpm and shaft torque were made with torsion meters already installed on the vessel, after the manufacturer certified at the yard that they were performing well within the 5% accuracy requirements.

4.3.4 Fuel Consumption

The fuel flow was measured by calibrated in-line turbine flow meters, calibrated and supplied by the Naval Sea Systems Engineering Station (NAVSESS) in Philadelphia. The meters were installed in the supply and return lines for both engines. Hoffer, Inc. (Model HO1X1-6-50-B-1M-F1SS) manufactured them. They have an advertised accuracy of 2% of the maximum measurable value. Two representatives from NAVSESS were present for installation and data collection.

4.3.5 Emission Measurements

The sheer size of the vessel posed some problems not encountered previously. At 600', it was 50% larger than even the largest US Coast Guard icebreakers (399'). It did have stacks, but they were about 40' off the main deck, and quite inaccessible for our instruments, not to mention operating personnel. The decision was to take the samples through a port in the exhaust about 2' above the engine.

The engine room spaces were luxurious compared to the small boats. There was ample room to mount the pollution instruments on flat surfaces within reach of the access ports. All instruments, (ECOM KDs) were hooked to an automated data collection system in the Main Control Room (a sound-insulated, air-conditioned room at the back of the engine room).

4.4 M/V KINGS POINTER (T-AGOS) [21]

4.4.1 General Background

The CG R&D Center and Maritime Administration next conducted testing on the M/V KINGS POINTER [1] to quantify the level of pollutants and to further explore portable emissions testing technology for shipboard applications - in this case with constant-speed diesel engines generating electric propulsion.

The information from this test was not only important as a measure of the emissions of this type of vessel, but also as a basis for later comparison with output from a similar vessel equipped with fuel cells as the main propulsion.

The KINGS POINTER was tested at the request of the Maritime Administration who operate the vessel, and who co-sponsored much of our emissions research under the U.S. Coast Guard/U.S. Maritime Administration Cooperative Research Program on Marine Engine Exhaust Emissions. Tests were conducted in May 1995 in the area of Long Island Sound just outside Great Neck, and Hempstead Harbor, NY.

The vessel is designated as a T-AGOS-2 (acoustic ocean surveillance vessel). Originally it was commissioned for the U.S. Navy as the USNS Contender, designed to tow a slow-speed acoustic hydrophone array in support of anti-submarine warfare. It was selected as a different type of platform, because it has diesel-electric propulsion. The diesel engines essentially run at constant speed (1200 rpm), and turn generators that run the electric propulsion motors. Output was given directly as kilowatts on the panel, so the calculations of emissions/kWhr were quite simple. A secondary reason for interest in this vessel is that it appeared to be an ideal platform for future testing of fuel cells for main propulsion. The electric motors would be in place and the fuel cell stacks would merely replace the diesel engines. At the time of the test a federal consortium was being assembled to conduct research leading to the year 2000 demonstration of marine fuel cell propulsion.

Only three of the four diesel engines are generally used - two for propulsion, and the third for on-board power generation. Tests were conducted on only the No. 2 and No. 4 engines (both on the port side).

4.4.2 Air Measurements

Each engine had two turbochargers. The inboard one of each engine was connected to Flowhood. The engine room air temperature was read on the Flowhood digital recorder, as was the barometric pressure. The relative humidity was measured with a Dickson Company Model THDX chart recorder located in the engine room.

4.4.3 Power Meters

The shaft horsepower meters were not used owing to some difficulties with the port engine. Instead, as mentioned above, the power was read directly in kWhr from the generator outputs.

4.4.4 Fuel Consumption

Fuel flow was measured with two Brooks, Model ER-11LHP positive displacement type flow meters installed on each engine - one on the input, and one on the return line. Positive displacement was used since the fuel was gravity-fed to the engines from a day tank located just

above the engine room. The flow meters were calibrated at 85 °F for use in the KINGS POINTER engine room.

4.4.5 Emission Measurements

Two different instruments took emission data: the ECOM-KL, and the ENERAC 2000E. They recorded the stack temperature as well as the emission analyses. The probes were inserted through a fitting installed through the exhaust insulating material, about 2' above the turbochargers. Both instruments were calibrated with span gases of certified concentrations in the laboratory prior to the field tests. In the field, they were recalibrated using portable gas bottles of certified concentrations. Probes were inserted into the gas stream for only ten-minute period of steady state operation so as to minimize carbon buildup in the probe tip.

The first sets of test data were collected on 12 April. There were a number of problems with the probe tips clogging, and the malfunction of one emission instrument, and the failure of the flow meters in engine 4, which resulted in the tests being aborted. They were rescheduled for 10-11 May 1995, and were successfully carried out then.

4.5 Commercial Tug COUGAR [22]

4.5.1 General Background

To expand, our variety of vessels, it was desired to test a commercial vessel. Following a presentation of the R&DC's exhaust emission work at PROPULSION '95 (sponsored by *Marine Log*), Maritrans offered the use of one of their tugs (the 105' COUGAR) that conveys oil barges from New Jersey to Connecticut. This gave the opportunity to test with and without barge, over longer distances. The testing was conducted in May 1996.

4.5.2 Air Measurements

As in other tests, the Flowhoods were attached to the turbocharger and provided air pressure and temperature as well as flow rate in cubic feet per minute (CFM).

4.5.3 Power Meters

The shaft torque was measured on both port and starboard shafts during each test run. The measurements were made with the Wireless Data Corp. Model 1642A as described in Section 3.1.4 [7].

4.5.4 Fuel Consumption

The novel feature in this test was that the Stellar Marine fuel management system (EMS-1000) was installed to measure fuel consumption, speed, and HP. The fuel consumption was determined with a potentiometer that recorded the fuel rack position calibrated to the fuel used,

and was recorded directly in gal/hr. The Stellar Marine engine speed pilot (ESP-1000) was also installed and required tapping into the throttle pneumatic system. Its function was to assess potential fuel savings.

The speed pilot is analogous to an automobile cruise control. It was purported to control the throttle in such a way as to balance engine outputs, and give more efficient operation with an overall fuel savings (as much as 10-15% in some instances). These instruments were installed on the Gateway 2000 laptop that engaged and disengaged the speed pilot on command. The results on the COUGAR, though not definitive, strongly indicated a fuel saving with the speed pilot engaged - enough to warrant further evaluation.

4.5.5 Emission Measurements

Originally, it was intended to use two ECOM KDs, so the data could be streamed to the EMS-1000 data logger. However, one malfunctioned and the ENERAC 3000E (an updated version of the 2000E) was substituted. This did not have the RS232 port to enable the data to go to the data logger, so only one was automatically recorded. It did, however enable a comparison of the ECOM KD by swapping between the two engines.

The ENERAC 3000E, with a temperature control on the electrochemical sensor to minimize cross-contamination readings in the NO and NO_2 values. The sensor's accuracy for NO, NO_2, and CO ppm readings on the ECOM KD [11], and ENERAC 3000E [12], are advertised as 5% and 2%, respectively.

4.6 Construction Tender KENNEBEC (WLIC-160) [23]

4.6.1 General Background

The construction tender KENNEBEC was the last vessel tested under this project. As such several objectives were tacked on to primary one of determining the emissions for the vessel. These included statistical comparison of two portable test instruments, comparison of alternative means of measuring power and fuel consumption, and finally an evaluation of an electronic control device to give fuel savings.

4.6.2 Air Measurements

The air pressure, temperature and humidity were measured in the vicinity of the air intake. Barometric pressure was recorded in the engine room on a Control Data digital recorder, as well as by each of the Shortridge Flowhoods. Air temperature readings were also taken from the Flowhoods installed on each inboard turbocharger (i.e. on one of the two turbochargers of each engine), and were confirmed against temperature readings available on the Control Data digital recorder and THDx chart recorder. The total air intake was obtained by doubling the reading taken from one side of each engine.

The Control Data digital recorder was checked against the University of Connecticut's Marine Science Institute Equipment. Relative humidity RH), air temperature and barometric pressure readings agreed within 4%/. RH was checked against the Dickson Company Model THDx humidity sensor in the engine room. All these data were recorded manually.

4.6.3 Power Meters

Both a strain gauge-based power meter, and a fuel consumption-based units were used in hope of getting a direct comparison, and to determine whether the strain-gauge measurements were really necessary in a streamlined emissions protocol which is very labor intensive. These comparisons have been made in the past with very good agreement on barges and ferries on the West Coast [9]. In fact, the Stellar Marine EMS-1000 is not subject to temperature variations that show up when the shaft heats up.

For some reason, the strain gauge calibrations were off for the Wireless Data device, so the power measurements from the EMS-100 were used in the calculations. The EMS-1000 operates on fundamentally sound principles, based on fuel consumption. It was used for testing six Coast Guard vessels [10], (although the device was not mentioned by name in that report).

During data reduction, a plot of the Wireless Data Vs EMS-100 readings gave linear curves - indicating that the Wireless Data was giving consistent readings proportional to the power, though the absolute readings were in error, i.e. there was nothing fundamentally wrong in principle - merely in the calibration.

4.6.4 Fuel Consumption

The Stellar Marine fuel management system (EMS-1000) was used, as on the tug COUGAR to measure the fuel consumption directly from the fuel rack. The Stellar Marine engine speed pilot (ESP-1000) was also installed with the fuel management system to record fuel consumption, engine horsepower, and provide a capability of balancing the engines for optimum running efficiency.

Both the EMS-1000 and ESP-1000 software were installed on a Gateway 2000 laptop. The laptop was used to engage and disengage the engine speed pilot. Obviously, fuel savings are of great interest to both industry and the Coast Guard. The evaluation of the ESP-1000 was to be accomplished on a not-to-interfere basis with the primary emission data collection.

4.6.5 Emission Measurements

Fittings were installed in the port and starboard exhaust stacks about a foot above the engine to accommodate ball valves. The ball valves were opened after steady-state stack temperatures were attained at which point the emission analyzer probes were inserted. Again, the ECOM KD, and the ENERAC 3000E were used for comparison of their capabilities. The readings were within +/- 5% after rechecking calibrations against the span gases after the test.

4.7 Additional Coast Guard Cutters Tested Under Contract [9]

4.7.1 General Background

Six Coast Guard cutters and patrol boats were tested for emissions by ETC under contract the Volpe National Transportation Systems Center (NVTSC), and the full details are reported in Reference [10]. The purpose of these tests was to survey vessel emissions to provide the Coast Guard with a database for air quality compliance planning and to update the emission inventory for selected USCG vessel classes operating under the jurisdiction of California Air Resources Board (CARB). Four of the tests were conducted on the West Coast; two in Key West because of vessel availability. A large icebreaker (399 Foot Polar Class) was to have been tested, but neither the POLAR SEA nor POLAR STAR was available for testing.

The six cutters tested were, in order of increasing size: 41318 (41' UTB); two 110' WPBs - the TYBEE and LONG ISLAND; STEADFAST, a 210' WMEC; THETIS, 270' WMEC; and the SHERMAN, 378' WHEC.

The emission-testing program included determination of particulate matter (PM), NOx, CO, SO_2, uncombusted hydrocarbons (UHCs), CO_2 , O_2, and plume opacity. Gaseous pollutant sampling was conducted using CEM instrumentation. Particulate emissions were determined with a "state of the art" Micro-Dilution continuous particulate sampler (Model BG-1 by Sierra Instruments). This 600 lb instrument was too bulky to be used on the 41' UTB.

Particulate matter sampling using EPA Reference Method 5 sampling methodology was deemed not applicable due to the limited amount of space on shipboard, and the exhaust pipe configurations not satisfying Method 5 criteria. Plume opacity observations by a qualified observer following EPA Method 9 procedures were conducted for those vessels where the plume from the exhaust stack was visible from the deck of the vessel (378' WHEC, 270' WMEC, and 210' WMEC).

4.7.2 Air Measurements

No air intake measurements, barometric pressure, temperature or relative humidity measurements are given in the report [10]. The only clue is the statement "For calculating emission rates, the exhaust gas flows were determined by monitoring actual fuel consumption and obtaining engine RPM/horsepower information during emissions testing." One can only speculate how the air/fuel ratio might have been determined with different engines and turbochargers.

4.7.3 Power Meters

the Stellar Marine fuel management system (EMS-1000) was used in all the tests to determine the fuel consumption and power.

4.7.4 Fuel Consumption

Fuel consumption was measured at the fuel racks by the EMS-1000.

4.7.5 Emission Measurements

Emission testing was conducted with instruments either mounted in a self-contained module place on the upper deck of larger vessels, or with instruments mounted in portable cases and operated from below deck for smaller vessels. Sampling locations followed EPA guidelines where possible, but in some cases there were space constraints, or insufficient length of straight exhaust pipe.

EPA Methods 3A (O_2/CO_2), 6C (SO_2), 7E (NOx), and 10 (CO) were used to quantify the emission at five different load conditions from the two diesel engines operating concurrently on each vessel. The same testing configuration was used for the emission testing of the gas turbine-equipped vessels.

All data were recorded in real time on two separate recording devices. A computer data acquisition system collected five-minute averages with a two-second sampling frequency. Data were also recorded simultaneously on multichannel (Linseis) continuous strip chart recorders.

4.7.6 Particulate Measurements

The PM was tested in accordance with ISO 8178-1 guidelines [2b] using a Sierra, Model BG-1 microdulution continuous particulate matter sampling and data acquisition system. This unit dilutes the entire sample fraction extracted from the exhaust stack. Dry, hydrocarbon-free air was metered into the chamber under pressure and mixed with exhaust gases in precisely controlled operator-selected ratios. The diluted sample was drawn through two pre-weighed 90 mm Pallflex (T60-A) filters, sealed and sent to the laboratory where it was dried to constant weight and the net weight of the PM determined.

4.7.7 Opacity Measurements

Opacities were estimated by EPA Method 9 for the large CG cutters: 378' WHEC, 270' WMEC, and the 210' WMEC. This is a somewhat subjective test requiring a qualified observer. The important variables that can be controlled are the angle of the observer with respect to the plume, and the sun, as well as the point of observation of the attached and detached steam plume. Uncontrollable variables include luminosity and color contrast between the plume and the background against which it is viewed.

Observations are typically made with the observer at a distance sufficient to provide a clear view of the emissions with the sun oriented in the 140° sector to the observer's back. Observations are made at the point of greatest opacity in the plume, with momentary observations at 15-second intervals for a minimum of 24 observations. They are recorded to the nearest 5% on a field data

sheet along with pertinent site and meteorological information. For each data set, the 24 observations are averaged and reported as the opacity.

4.7.8 Unburned Hydrocarbons

These were determined using EPA method 18. Integrated samples were collected in new Tedlar bags, purged twice with exhaust gases, and then closed. They were sent to a laboratory for gas chromatographic separation of C1-C6 hydrocarbons.

5.0 Results

5.1 Summary of Shipboard Tests

5.1.1 Vessels Tested - **Table 7 - Vessels Tested and Propulsion**

Test No.	Vessel	Class	Engines	Rated HP	Rated SRPM	Date	Location
TESTED BY USCG R&D CENTER							
Point Class Patrol Boats							
1	Point Francis	82' WPB	Caterpillar D3412750-800	700	2100	8/13-16/93	NL, CT
2	Point Brower	82' WPB	Caterpillar D3412750-800	700	2100	9/28-30/93	SF, CA
3	Point Turner	82' WPB	Caterpillar D3412750-800	700	2100	11/17,8/93	Newpt RI
4	CG-47201	47' MLB	Detroit Diesel 6V-92 (DDEC Mod)	425	2100	11/8-12/94	Cape May NJ
5	USS Ashland	600' LSD	Colt-Pielstick PC2.5V16	8480*	520	2/14-16/95	Norfolk VA
6	M/V Kings Pointer	224' T-AGOS-2	Caterpillar D398TA	970	1200	4/12/95	Long Is Sound
7	Cougar	105' Tug	Caterpillar D399	950	1200	5/13/96	NJ-CT
8	Kennebec	160' WLIC	Caterpillar D378	500	1225	11/12/96	Portsmouth VA
TESTED BY ETC UNDER CONTRACT TO NVTSC							
9	Steadfast	210' WMEC	Alco 16V-251B	2000	1000	4/18-20/95	Astoria OR
10	Sherman	378' WHEC	Fairbanks-Morse 3800 TD 8 1/8 + Pratt & Whitney FT 4A-2 Gas Turbine	3500 (18,000)	800	4/30-5/2/95	Oakland-SD, CA
Island Class Patrol Boats							
11	Tybee	110' WPB	Paxman 16 RP 200 M Valenta V-16	2880	1500	5/23-25/95	SD CA
12	Long Island	110' WPB	Caterpillar 3516 DITA V Type	2740	1910	5/31-6/2/95	Monterey CA
13	Thetis	270' WMEC	Alco V-18 251C	3650	1025	6/23-5/95	Key West FL
14	CG-41318	41' UTB	Cummins VT-903	590	2550	6/26,7/95	Key West FL

- For the USS ASHLAND, the 8480 bhp is based on a rated horsepower of 530 bhp per cylinder (16 cyls) at a rated speed of 520 rpm. However, in actual tests the maximum power measured was 7642 at 528 rpm.

5.1.2 Exhaust Emissions (R&DC Tests)

Table 8 summarizes the results obtained by R&DC testing. The results of the first boats tested are reported in Reference [5], in which the data were reduced and calculations made by the ISO-recommended procedure [2c]. A material balance calculation was evolved, giving somewhat different results (See Section 5.3 for discussion on calculations). In principle it is more rigorous, and was used on all later results.

Table 8 - Exhaust Emissions
Vessel Tested by USCG R&D Center

Test No.	Vessel	NOx g/kWhr		CO g/kWhr		SO_2 g/kWhr	
Point Class Patrol Boats[a]							
1	Point Francis	10.0		2.0		ND	
2	Point Brower	8.0P, 3.0S		3.0		ND	
3	Point Turner	10.0		2.0		ND [c]	
4	CG-47201[b]	11.7		4.73		3.17	
5	USS Ashland[c]	13.99		1.79		-	
6	M/V Kings Pointer (Engines #2 and #4)	2	4	2	4		
		7.07	11.71	3.47	2.94	ND	
7	Cougar[d]	P	S	P	S	ND	
		4.62	5.23	0.38	0.36		
8	Kennebec[e] (Port and Starboard)	P	S	P	S	P	S
		13.28	4.11	1.91	0.76	0.80	2.88

[a] Based on ISO calculations [5]
[b] Only port engine, and only at rated speed (2100 rpm) [19]
[c] Averaged over six operating points (speeds) with single engine/shaft except at 165 rpm (see Table 9) [20]
[d] Tug with full barge, port and starboard [22]
[e] Port and starboard varied widely - primarily because of low ENERAC readings on starboard engine [23]

The duty cycle selections for the ASHLAND were selected from an extensive study made by Markle [25]. He studied the logs of several LSDs to obtain their actual duty cycles. These data could provide a ready way to compute emissions without having to test each vessel.

Table 9 - Duty Cycles for USS ASHLAND

	1	2	3	4	5	6
Speed	100	70	62	40	38.8	idle
Power	100	66.3	45.9	13.1	6.3	2.3
Weighting Factor	0.06	0.23	0.14	0.25	0.22	0.10

Levels 1-5 were measured with only engine MPDE 1B on the shaft; level 6 with engines MPDE A and B on shaft. Shaft rpm varied from 221 to 528; power from 180 hp to 7,642 bhp

5.1.3 Exhaust Emissions (NVTSC/ETC Tests)

The NVTSC/ETC testing involved six vessels in five classes that are in operation in California. They did not test the Polar Class icebreakers because they were unavailable, and they did not test the Point Class patrol boats, because they had already been tested (including the Point Brower in San Francisco).

The tests were very ambitious in that they were to include (where possible) the measurement of particulates, and of opacity (on those vessels with smokestacks above deck). The test points used were nominally those of ISO 8178 Part 4 cycle E5 which includes five speeds as in cycle E4 (Shown in Table 4 on page 15). However, the values are the same as in ISO 8178 cycle E3 (See Table 3, page 14), but with the addition of the idle speed. The only difference between E3 and E5 really is the weighting factors used, since a fifth point is added.

In actual testing, the speed is the easiest to set, so that is generally what is done, and the resulting power measured. The nominal power values used in the data acquisition by NVTSC/ETC are shown in Table 10 below for CGC STEADFAST. The power measurements deviated so much from the nominal values, that the weighting factors were not representative of the ship duty cycle. Therefore, only the emission values at full speed are reported as seen in Table 11. This is adequate for comparison of relative values of the emissions of different vessels. In fact, CARB originally accepted the emissions at rated speed and power as a measure of emissions for regulatory purposes.

Table 10 - ISO 8178 Mode Number Cycle E5
Used by NVTSC/ETC

	1	**2**	**3**	**4**	**5**
Speed, ISO (%)	100	91	80	63	idle
Power, ISO (%)	100	75	50	25	0
Power, ETC (%) Steadfast[a]	100	38.5	14	6.5	2.1
Weighting Factor	0.08	0.13	0.17	0.32	0.30

[a] Actual power measurements found on CGC Steadfast (avg. for port and starboard engines)

Table 11 - Exhaust Emissions (at 100% Speed)
Vessels Tested by NVYSC/ETC

Test No.	Vessel	NOx g/kWhr	CO g/kWhr	CO_2 %	SO_2 g/kWhr	O_2 %	UCH g/kWhr	Part g/kWhr	OP %
9	Steadfast	18.7	0.83	6.04	1.66	13.1	0.59	0.81	10
10	Sherman	9.31	1.18	5.46	0.12	13.1	0.07	-	-
	Island Class Patrol Boats								
11	Tybee	9.04	5.99	8.86	0.83	8.57	-	0.30	-
12	Long Island	11+/-1[a]							
13	Thetis	12.0	1.38	6.73	1.65	11.7	0.04	0.14	5[b]
14	CG-41318	6.85	0.89	8.28	0.98	10.7	0.02	-	-

[a] Estimated by extrapolation (100% not tested)
[b] Double at idle, i.e. 10.

5.1.4 <u>NOx Emission Summary</u>

The proposed international guidelines for NOx emissions [26] are based on the engine rpm. (See Fig. 3 below). The allowance is constant at 17 g/kWhr for low speed engines (<130 rpm); 9.84 g/kWhr for those above 2000rpm. For intermediate engine speeds, the proposed limit is given by the equation:

$$\text{NOx Limit (g/kWhr)} = 45 \times n^{-0.2}$$

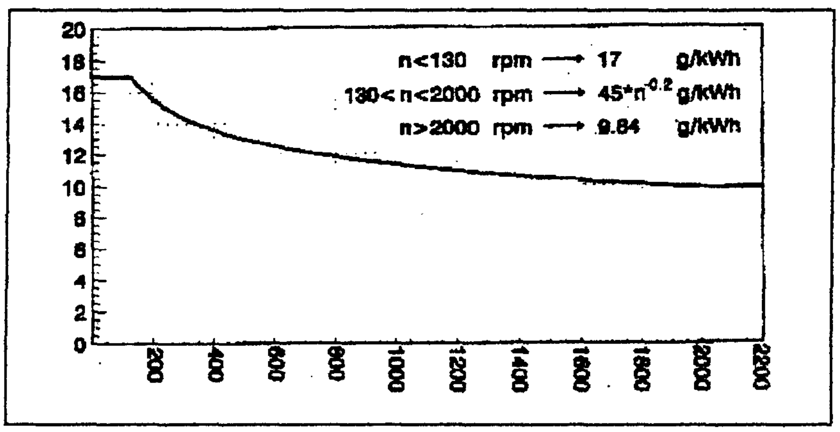
From this equation and the rated engine rpm, the Proposed NOx limits were computed for Table 12 below. A primary purpose in these studies was first to establish what the actual emission levels were, and secondarily to quantify the extent of excess emissions to make better judgments regarding amelioration.

Table 12 - NOx Emissions (g/kWhr)
Proposed Limits vs. Found*

Vessel	NOx Proposed	NOx Found	Vessel	NOx Proposed	NOx Found
R&DC TESTS			**VNTSC/ETC TESTS**		
82' WPBs (3)	9.84	**~10**	Steadfast	11.3	**18.7**
47' MLB	9.84	**11.7**	Sherman	14.8	9.3
USS Ashland	12.88	**14.0**	Tybee	10.42	9.0
Kings Pointer	10.90	**11, 7**	Long Island	9.97	**11.0**
Cougar	10.95	4.9	Thetis	11.25	**12.0**
Kennebec	10.84	**13**, 4.1?	41' UTB	9.84	6.9

- Those in bold print are those above proposed limits - representing 75% of boats tested.

NOx (g/kWhr)



Rated Engine Speed (rpm)

Figure 3. NOx Limit Curve for Marine Diesel Engines [26]

5.2 Emission Analyzers

5.2.1 "Portable Instruments"

The most recent shipboard studies of exhaust emissions for slow and medium speed shipboard propulsion systems were reported by Lloyd's Register [2]. They worked under international sponsorship and reported results to the IMO.

The instrumentation consisted of sampling probes in large vessel smoke stacks, with heated probe and sampling line leading to gas conditioning units, and a gas chromatograph (GC) for hydrocarbon analysis using a heated flame ionization detector. This is in series with a non-dispersive infrared (NDIR) spectrophotometer for NO, SO_2, CO and CO_2 , measurements. Also included was a paramagnetic oxygen analyzer. A data acquisition system took data from a fuel rack position sensor (for fuel consumption), charge air pressure sensors before and after the turbocharger cooler, mass flow sensors in the stack, an exhaust temperature thermocouple, as well as a shaft rpm and torque transmitter.

This equipment is similar to that used by the U.S. EPA and others, but was very bulky. In addition the gas chromatograph requires a carrier gas and hydrogen gas for the flame. The latter is not only bulky, but can be hazardous.

Commercially available portable instruments, based on electrochemical sensors, can replace the bulky GC, NDIR and oxygen analyzers with a unit the size of a briefcase. Three of these were employed for the Coast Guard's laboratory and shipboard testing.

For the portable instruments to be acceptable, they must be shown to be equivalent to other methods, and to each other. Accordingly, they were compared at every opportunity, and found to give acceptable results. In fact, the ENERAC 3000E was accepted for the EPA's Conditional Test Method (CT-022) for NOx [15].

5.2.2 Portable Instruments Used

In the present study, there were four instruments used. They were: the Lancom 6500 manufactured by Land Combustion, the ENERAC 2000E and ENERAC 3000E manufactured by Energy Efficiency Systems, Inc., and the ECOM KD manufactured by ECOM America. Basically, they all measured: oxygen in the range of 0-25%; CO in a choice of low range (0-2000 ppm) or high range (0-40000 ppm); SO_2 and NO in the range of 0-2000 ppm, and NO_2 in the range of 0-1000 ppm. They also measured stack temperature, and calculated CO_2, efficiency and excess air. Accuracy was +/- 1 % for oxygen, and +/- 4% ppm Lancom; +/- 2% for ENERAC. Resolution was +/- 0.1% of oxygen; +/- 1 ppm for other gases.

The Lancom 6500 was used in studies at the US Coast Guard Academy, and aboard the 82' WPBs. The ECOM 2000E was also used aboard the 82' WPBs, and at MIT where it was

compared with the MIT "gas cart". Later it was upgraded to the ENERAC 3000E and used for later ship testing and tests at PSU and aboard the COUGAR and KENNEBEC. The ECOM KD was the last instrument bought for last ship tests, because of the ease of interfacing directly to a data management system.

The ENERAC 3000E was the result of several years of intensive study by the manufacturer to address concerns of the EPA on the use of electrochemical sensors. They obtained a through understanding of the principles that affect the performance, including: adsorption, desorption, Fick's Law, Arrhenius' Law, Boyle's Law, Faraday's Law, gaseous diffusion laws, etc. They developed an adequate electrode reserve capacity, better filter performance, temperature control, and a calibration protocol in the various sensor ranges. The resulting product satisfied the US EPA, who published the new NOx Conditional Test Method [15], as equivalent to the traditional Reference Method 7E [27]. This was originally applicable to boilers, **engines,** turbines, and heaters.

5.2.3 MIT Study - ENERAC vs. "Gas Cart"

As mentioned in Section 3.2.2, MIT uses a "gas cart" six feet wide, six feet high and 3 feet deep. It is on wheels, so can be moved in a laboratory environment. The gas cart also required an accompanying cart about the same size to carry the necessary gas cylinders. The cart has two Beckman Model 865 infrared instruments to measure CO and CO_2. It also has a Beckman Model OM-11 EA oxygen analyzer which employs a polarographic technique (dropping mercury electrode). Finally, a chemiluminescence instrument is used to measure NO and NOx.

This cart was compared directly with the ENERAC 2000E by leading the heated gas sample line outside the engine cell and alternating the sampling between the gas cart and the ENERAC. There were some differences noted that were finally attributed to a leak in the internal gas lines of the gas cart. In other words, the ENERAC gave better results, and also alerted the users of the gas cart to a problem.

5.2.4 Stability Comparison ENERAC 3000E vs. ECOM KD on Shipboard Tests

Two different portable emission analyzers (the ENERAC 3000E, and the ECOM KD) were compared in two ship tests: the tug COUGAR, and the construction tender KENNEBEC. The ENERAC Model 3000E is purported to give more reliable NOx readings, based on its design incorporating a thermal control to eliminate cross contamination, provide multiple sensor ranges, and adsorption losses.

For the tug COUGAR, calibrations of both instruments were conducted on 11 November. They were calibrated to the nominal span gas values. About four days after the tests, the span gases were remeasured at the CG R&D Center, with the results shown in Table 13 below:

In this test, there was more disparity with the ENERAC (about 10% off for oxides of nitrogen), than with the ECOM (1-3% off for oxides of nitrogen).

Table13 - Instrument Readings after COUGAR Test (originally calibrated to nominal span gas values)

Gas	ECOM-KD		ENERAC 3000	
	Rdg (ppm)	Cal Gas	Rdg (ppm)	Cal Gas
CO	815	751	625	751
NO	1120	1034	923	1010
NO_2	101	104	450	500
SO_2	470	512	-	-

For the KENNEBEC (see TABLE 2, p12), as in the COUGAR tests, both analyzers were calibrated before the start in accordance with their respective manuals [8] and [9]. The essential point from these tables (2 and 13) is that there are still some problems with calibration and/or drift of the instruments, and further comparisons are warranted. If care is taken in calibration and monitoring drift either instrument gives reasonable results for relative emission measurements..

5.3 Calculations

Calculation of the emissions is a formidable task. All analytical instruments measure concentrations of pollutants. In order to relate these concentrations to actual quantities, it is necessary to obtain the total flow of the exhaust. This can be done directly; it can be done by estimating air flow from the engine, based on displacement and the turbocharger while measuring fuel consumption, or it can be calculated by a complete material balance by measuring the air and water vapor flowing in and the fuel consumed to calculate the exhaust flow. The latter is more tedious, but also more rigorous.

5.3.1 Lloyd's Register [2]

The exhaust sampling system used by Lloyd's Register [2] is shown in Figure 4.

The schematic diagram in Figure 4 was used for transient measurements. For the steady state work, the exhaust was measured directly by placing a mass flow controller in the vessel's smokestack. A sampling probe was placed across the inside of the stack at right angles to the flow, and a minimum distance down of 1 meter, or three stack diameters. This procedure is not possible with small boats that pass their exhausts through the transom, and some have aqueous injection, which complicates the sample drying procedure.

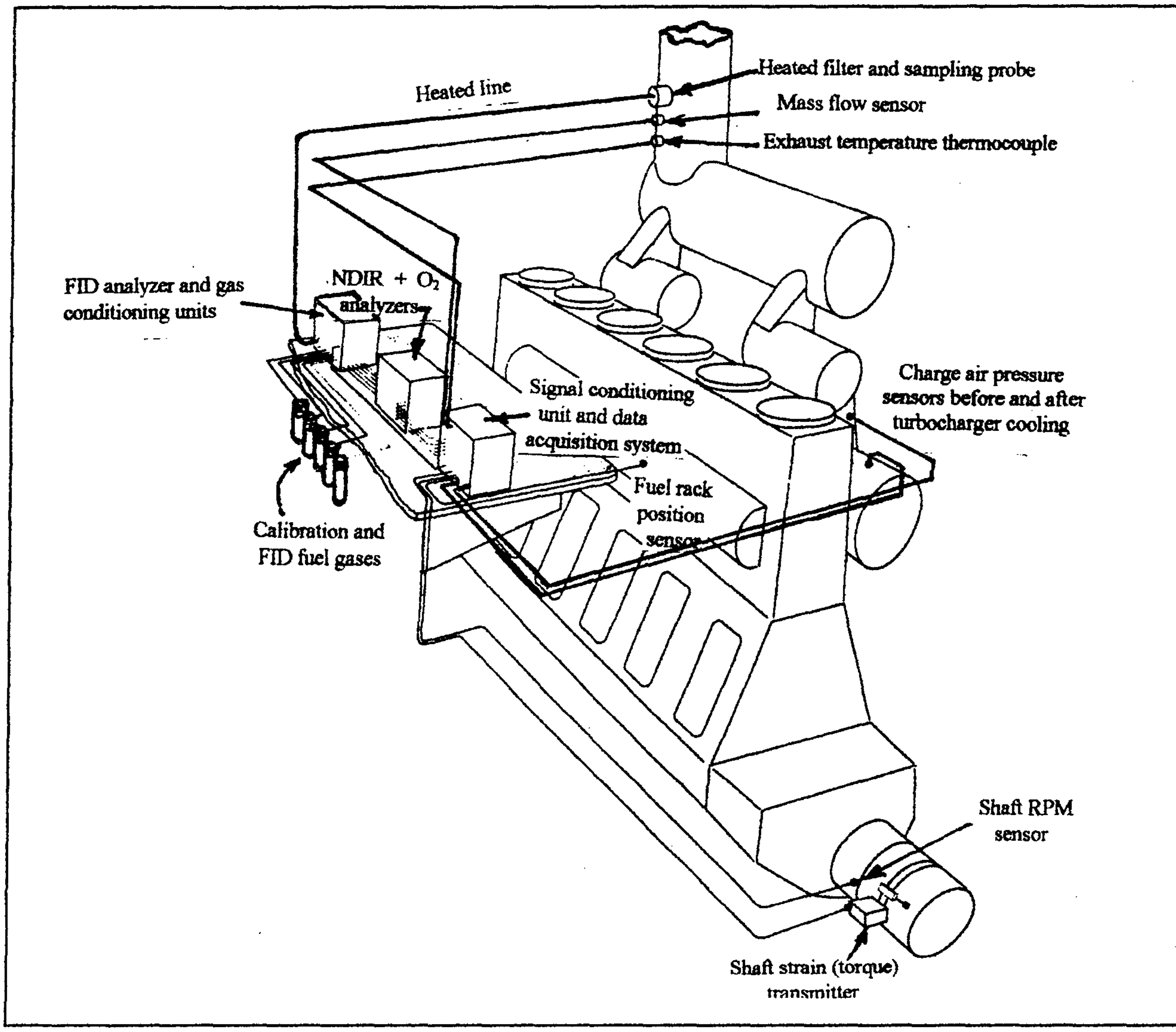


Figure 4. Schematic of Lloyd's Register Data Sampling System

The calculations are outlined in Figure 5 above. In those instances where the input data of fuel flow and/or engine power were not directly available from the ship's own instrumentation, the exhaust mass flow for the test engine was established using the engine manufacturer's performance and fuel consumption data in conjunction with the trial records for engine setting, rack position, turbocharger speed, exhaust gas temperatures, and propeller characteristics determined from hydrodynamic calculations. The emission factors relating to NOx were based upon measured NO. This assumed little discrepancy between NO and NOx at the point of sampling - "based on the assumption that NO is likely to form approximately 90-95% of the total NOx at the point of exhaust discharge."

5.3.2 USCG R&D Center

The CG R&D Center calculations are based on a stoichiometric balance of incoming fuel and air with the exhaust. Unlike the Lloyd's Register calculations, the NO_2 was measured as well as the NO to determine NOx. The basic assumption is that there is more than sufficient oxygen available in the entering air to effect complete combustion of the fuel components in the engine. For the material balance, the quantity of air per unit time (including water vapor), and the quantity of fuel per unit time account for all incoming materials.

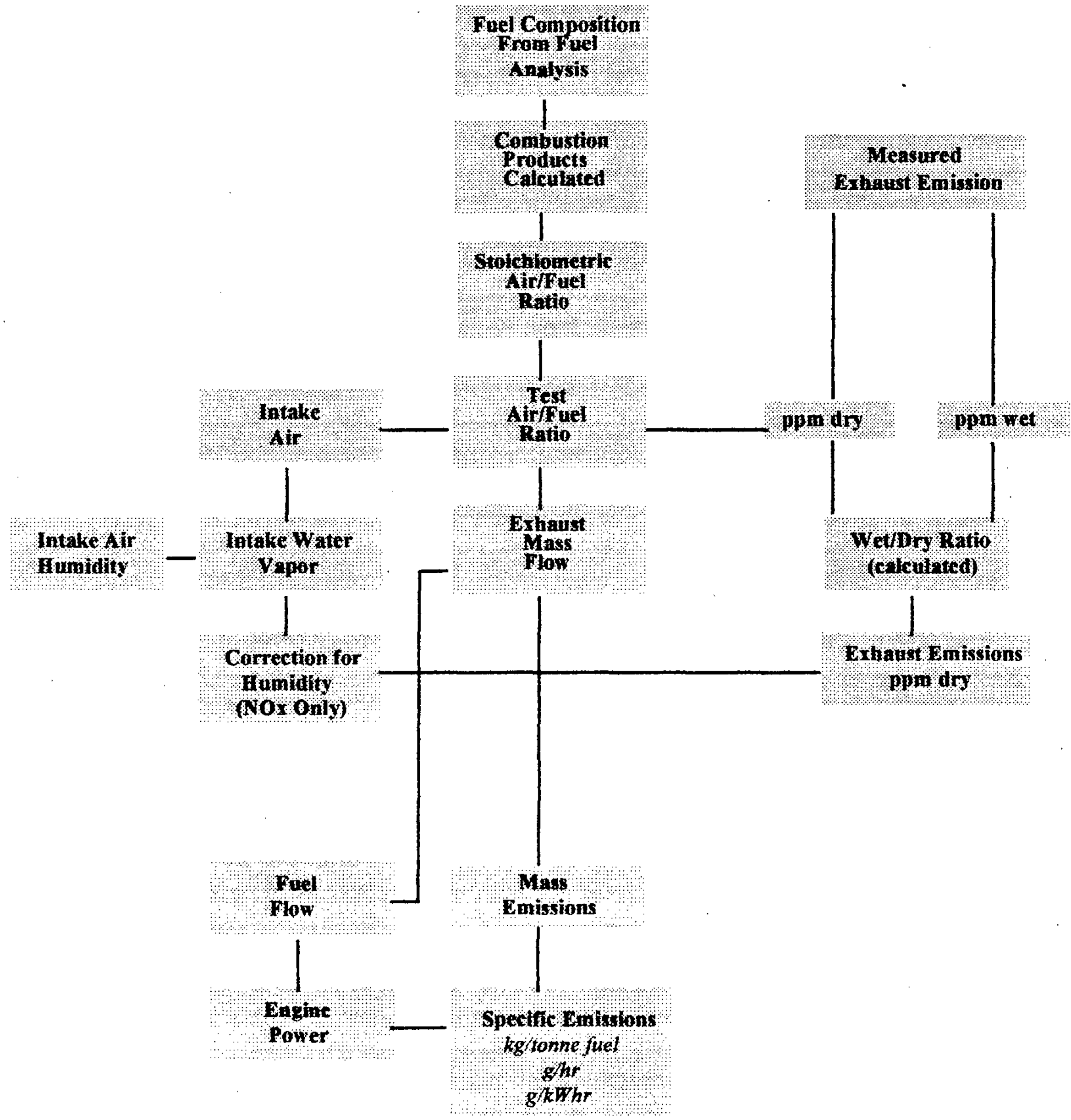


Figure 5. Outline of Lloyd's Register Calculation Procedure

The initial assumption of complete combustion assumes all of the carbon in the fuel is converted to CO_2. The measurement of CO allows the recompilation of the total CO_2, with slight additional O_2 that results from the partial combustion.

A sample calculation for the KENNEBEC operating at maximum speed is given in Appendix A. All calculations are on a pound-mole basis. Units are shown to clarify the conversions. See KENNEBEC report [23] for full details.

5.3.3 IMO/ISO [3]

In the recommended procedure by ISO/DP 8178 [3d], the exhaust gas flow can be measured by any one of four methods: 1. Direct gaseous flow measurement as done by Lloyd's Register [2]; 2. Air and fuel measurement as done by the R&D Center [23]; 3. Fuel consumption and exhaust gas concentrations are used to calculate the exhaust mass by the carbon and oxygen balance measurement - also included in the R&D Center method; 4. A total dilute exhaust gas flow (not used in any of methods reported here.

The calculations are outlined in Appendix B.

5.3.4 ETC Calculations [10]

The calculations used by ETC are based on the third method listed in 5.3.3 above - namely fuel consumption, and using the BTU values of the fuel. These assumptions obviated the need for airflow, pressure, relative humidity, etc. to be monitored. The equations used are given in Appendix C, and include those used for particulate calculations.

5.3.5 MAR, Inc. Calculations

The calculations used by MAR, Inc. are based on ISO 8178 carbon balance method, more are less (See Appendix D). Using the carbon balance approach to determine exhaust mass flow, the intake airflow is generally not measured. However, since the 82' WPBs airflow measurements were available the data analysis was greatly simplified.

5.3.6 MIT Model

The MIT study [20] had a partial objective of validating a predictive model propounded in an earlier thesis by Markle [25]. Markle did an exhaustive study from the logs of four LSDs, covering 11,500 hours of operation. He analyzed the data to develop a 27-point class operating profile for the LSD-41 Class vessel. A procedure combining ship hull form characteristics, ship propulsion plant parameters, and ship operating profile was detailed to derive an 11-mode duty cycle representative for testing the LSD-41 Class propulsion engines. The 11-mode duty cycle better predicted ship propulsion engine emissions compared to the 27-point operating profile propeller curve. In fact, Markle compared nine different profiles for predictive models Based on

the fuel consumption, and engine specifications, he calculated the NOx emissions. This approach, incidentally is used by many engine manufacturers - not only for existing engines, but those still on the drawing board.

Testing of LSD-48 was an attempt to validate the predictive model, since that approach could obviate the labor intensive and costly testing that has been described in this report. However, Markle used contour plots of the Colt-Pielstick PC4.2B engine (since they were unavailable for the Colt Pielstick PC2.5V16 engines on the LSDs). The PC4.2B is a much larger engine with 1630 bhp per cylinder vs. 530 for the PC2.5V. The result is that the measured emissions could not properly be compared with the predicted ones - since they were from two different engines.

The NOx specific emissions were determined in two different ways and compared. In the first, the molecular weight used in the calculation represented a weighted average of the combination of NO and NO_2. From the literature, it was estimated that the NO_2 would comprise ten percent of the total. (This is similar to the assumption made by Lloyd's Register in Section 5.3.1). The calculation was repeated, computing the specific emissions for each individually and summing the results. Either method offers possibilities for introduction of errors, yet each provided results within 5% of each other. The first method, using a weighted average molecular weight was selected for the presentation of the data. All MIT NOx emission results were calculated in g/bhp-hr, rather than g/kWhr.

5.4 NOx Emissions

Originally, CARB called for NOx emissions to be "normalized" to 15% oxygen in the exhaust. The purpose was to provide a common basis for comparison of different engines. This is accomplished as follows:

$$\text{Norm}_{mE} = \frac{\text{Meas'd}_{mE}\ (20.9 - 15.0)}{(20.9 - O_{2Ex})}$$

Where: 20.9 = % of oxygen in air (by volume)
Norm_{mE} = Normalized value of gaseous emission
Meas'd_{mE} = Value measured (or computed)
O_{2Ex} = Actual oxygen reading in exhaust

Our experience with marine diesel engines showed that normalizing to 15% in the exhaust as recommended, generated artifacts that distorted the true picture. When oxygen levels exceed 15%, it gives pollutant concentrations apparently larger than measured - as can be seen in Figure 6 below:

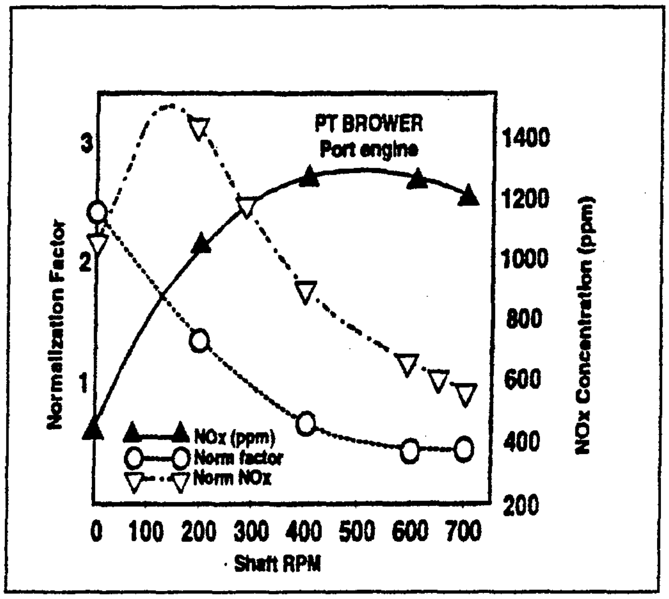


Figure 6. Normalized NOx Emissions for Point Brower Port Engine

The actual NOx emissions are seen to peak at about 500 srpm. The normalized values peak at about 180 srpm (near clutch speed) which is obviously wrong. In addition, the maximum, as pointed out above is larger than any measured value of the NOx. We believe this is artificial distortion of the data is dangerous, and strongly recommend reporting the NOx in g/kWhr as a truer measure of emissions (rather than as a concentration in the exhaust).

5.5 Effect of Water Depth

In shallow water, there is a buildup of water around the hull (sometimes referred to as "squat"), which increases resistance, thereby requiring some more power to achieve the same speed. This in turn would be expected to result in higher emissions. The test plans for the three 82' WPBs included some "shallow" water testing. The shallow water testing was conducted at 30' depths; the deep water testing was at approximately 120' depth. The 30-foot depth contributed very little extra loading, and the effect of depth was found to be negligible. [5, p 6].

5.6 Fuel Analysis

Elemental fuel analysis is essential for any material balance calculations, although marine diesel fuels have a relatively narrow range of composition, compared to other petroleum distillates. In fact, the emissions instruments use the values for a generic diesel fuel for the algorithms that compute the carbon dioxide formed. The analyses obtained are shown in Table 14.

Table 14 - Fuel Analyses for Ships Tested

	Point Francis	Point Brower	Point Turner	47' MLB	LSD -48	Kings Pointer	Cougar	Kennebec
Carbon (%)	86.38	86.10	85.95	87.01	86.09	86.33	86.86	86.85
Hydrogen (%)	13.43	11.60	12.77	12.59	12.97	12.44	12.97	13.02
Nitrogen (%)	<0.02	0.36	0.02	<0.02	0.06	0.02	0.02	0.22
Oxygen (%)	<0.02	-	0.02	0.11	0.02	<0.02	0.02	0.02
Sulfur (%)	0.14	0.11	0.047	0.14	0.38	0.17	0.15	0.03
Ash (%)	0.00015	0.0002	0.00072	0.005	0.001	0.005	0.001	<0.001
Water and Sed (BS&W) (Vol%)	0.02	0.0	<0.01	0.0	0.025	0.05	0.0	0.05
API Gravity (60° F)	-	34.1	34.9		35.3	32.4		
Density	0.825	0.855	0.840	[0.855]	0.848		[0.8495][a]	[0.8495][a]

[a] Approximate density of standard diesel fuel.

There is relatively little change in the hydrocarbon composition, although the variability of the hydrogen is an order of magnitude greater as seen in Table 15.

Table 15 - Variability in Fuel for Ships Tested

	Mean (%)	Std. Dev.	Relative Change (%)
Carbon	86.45	0.408	1.23
Hydrogen	12.72	0.544	11.1

Sulfur dioxide emissions are controlled exclusively by the composition of the fuel, i.e. it cannot form if there is no sulfur there. Generally low sulfur fuels are considered those with <0.20% S. This is not true with nitrogen, however, since nitrogen from the air can be incorporated into NOx during the combustion process.

There is, however another source of sulfur. That is in the lubricating oil. Therefore, the contribution of lubricating oil to emissions is of interest. This was addressed at MIT by Schofield [28], and Jackson [29], and is discussed in Section 7.2.4.

5.7 Fuel Savings

It is axiomatic that any fuel savings will result in lowering the overall emissions. The Engine Speed Pilot (ESP-1000) has a well-documented record of achieving fuel savings with ferries, barges and Great Lakes carrier by balancing the power to each propeller, and then optimizing the rpm for maximum speed. It functions much as a cruise control on an automobile. Often, full throttle consumes more fuel, but because of the hull speed it does not result necessarily in higher speed through the water than somewhat lower shaft speed. The Speed Pilot seeks out the highest vessel speed at the lowest engine speed.

Attempts were made on the COUGAR, and the KENNEBEC to test the efficacy of the ESP-1000. The Cougar test [22], the engine speed pilot was on for 2.7 hours, and off for 9.0 hours. The gallons per mile were averaged with the results of 5.8 gal/mi when the engine speed pilot was engaged versus 8.2 gal/mi when the Engine Speed Pilot was not used. This represented savings of 2.4 gal/mi (or 29.3%). This is considerably higher than the expected savings (10-15%), and certainly warranted further testing.

When applied to the KENNEBEC, the tests with the Speed Pilot allowed it to control the vessel for only 4-5 minutes at a time. Ideally to let it get in full control, it should be in control at least half an hour. Back to back tests at 74, 87 and 98% full rpm gave data over an 8-minute range. These skimpy results indicated a slight increase in power per unit of fuel consumed (about 1.5%). Although these results are unspectacular, they are in the right direction, and again suggest that further evaluation should be conducted.

6.0 Proposed Test Protocol

At the beginning of the project, it was envisioned that a detailed test protocol would be written and provided to both the EPA and IMO for consideration as standard shipboard test methods. From the foregoing, we have seen a diversity of approaches to measurement of power, fuel flow, etc., as experience and newer state-of-the-art measuring devices have become available.

In lieu of a detailed protocol in the form of ISO 8178, this section will deal with the elements recommended for such a protocol, based on the experience to date.

6.1 Test Plan

The first step in shipboard emission testing is to write a detailed Test Plan. Before a meaningful test plan can be written, it is necessary to do a "ship check." This involves identifying the vessel to be tested, and establishing the availability of the proposed test platform for the requisite time of the test, plus 1-2 days before and after for installation and removal of the test equipment. During the ship check, the location and accessibility of all installation points (similar to those shown in Figure 4), need to be identified. All existing shipboard facilities, including any speed, power, rpm, fuel consumption, GPS, etc. should be identified. In addition, locations for sampling of exhaust, airflow, fuel consumption, etc. should be identified. Consultation with the skipper

and/or chief engineer is required to clarify everyone's role and any crew assistance that might be needed during the tests. This includes communication from bridge to engine room to coordinate the test conditions.

The test plan should follow, as closely as possible, the ISO recommended Mode to be used - including the 4 or 5 speeds that are to be used. Several replicates should be conducted for each speed, with the test sequence established by a random number table.

Test plans will vary in details, but a number of elements should be considered, as shown in Table 16.

Table 16 Elements of the Test Plan

OVERVIEW

1. **Introduction** - with some background, and a statement of purpose.
2. **Participants** - a list of participants, including the test director and all others along with their specific duties. This includes any responsibilities and/or duties of crewmembers.
3. **Preparation** - a detailed explanation of preparation required; logistics of shipping equipment, calibration gases, etc.
4. **Installation** - installation of power recording devices (fuel rack or shaft), air measuring devices, test equipment, data acquisition system, etc. (1-2 days)
5. **Test Activities** - data collection duties - manual and electronic, bridge commands to engine room. (1-2 days underway).
6. **Experimental Design** – Establish sequence of data acquisition so that it can be analyzed statistically.
7. **Data Analysis** - identify who will handle data, and how data reduction will be conducted.

INSTRUCTIONS

1. **Time Frame** - Date of installation, and testing. Time standard to be used (e.g. EST of GMT-6hrs).
2. **Test Area** - Location of test trials, based on charts for traffic, depth, etc.
3. **Emission Data Collection** - identify instruments to be used, equipment and gear needed.
4. **Calibration Procedures** - specify how to be conducted, before, during and after tests.
5. **Safety Considerations** - based on ship's course and speed; safety of personnel and operation of engines within normal ranges. Safe operation is the responsibility of the ship's crew and takes precedence over test objectives.
6. **Pre-Departure Checklist** - Prepare a list including fuel sampling, instrument installation, equipment calibration, crew brief, etc.
7. **Test Completion Checklist** - including removal of test equipment, and restoration of engine configurations to original state (e.g. replace air filters, plug exhaust stack fittings)
8. **Communications** - Telephone, VHF radio and onboard links.

6.2 Emission Test Equipment

Based on the concerns of CARB and the EPA, NOx and particulates are the two primary emission products of concern. It has been reported that as many as 60,000 deaths per year in the US are

attributable to particulates [30]. The portable test instruments described in this report determine CO, NO, NO_2, SO_2, unburned hydrocarbons (UHCs), stack temperatures, excess oxygen, and computed values of CO_2, as well as NOx.

In major engine laboratories, large dilution tunnels are available for determination of particulate matter (PM). This is impossible in most vessels. However, the BG1 Microdilution Tunnel offers a "portable" method that gives good results. This instrument was first used in these studies at MIT where the 600lb weight and bulkiness were not deterrents. The studies on larger vessels by ETC used the same instrument. With enough demand, development would be warranted to remove the top portion of the instrument containing a bulky computer and substitute a laptop, thereby making it more truly portable, and significantly lighter.

6.3 <u>Power Meter Recommendations</u>

Measurement of shaft horsepower using strain gauge installations has been employed by the CG R&D Center for the last two decades when instrumenting various Coast Guard vessels for test & evaluation (T&E). It has proven to be reliable and consistent over the years. It is, however, a time consuming and demanding procedure that requires a skilled technician. Meticulous care is taken to prepare the shaft for strain gauges as well as the system setup. This process can take from 12 to 24 hours depending on accessibility of the shafts.

The Stellar Marine Inc. EMS-1000 system is an alternative means of determining *in-situ* power of main diesel engines. Although this equipment, like any other, is heir to mechanical or electronic problems, it is as reliable as the strain gauges, and far easier to install and use. It does not require knowledge of the shaft steel composition, surface problems, misalignments, nor temperature effects on the readings.

6.4 <u>Fuel Measurement</u>

Based on our experience with various devices, by far the simplest is that based on fuel rack injections. This measures precisely the fuel injected into the cylinder without having to install in-line meters to feed and return lines and computing net consumption.

6.5 <u>Air Flow</u>

Properly calibrated Shortridge Flowhoods have been found quite satisfactory for air flow, temperature and pressure readings - for modest sized engines (up to about 1000 hp). The differential Pitot tube worked well for the 8000 hp engine with a large intake.

There are various reliable instruments on the market for measuring relative humidity and barometric pressure.

7.0 Miscellaneous Related Research

A number of areas were examined within the scope of this marine diesel exhaust emission reduction project, including such things as dual fuel and fuel additives. Below is a brief review of these sub-projects.

7.1 US Coast Guard Academy (CGA)

The Engineering Department at the CGA cooperated by providing two test engines in their laboratory for some research project. The diesel CFR engine (normally used for determining cetane ratings) is an ideal research engine because the compression ratio and air intake can be varied quite easily. It was hooked up to permit mixing natural gas with the diesel fuel up to an 80/20 ratio. The SI engine was fitted to permit the use of propane as fuel. This latter capability was not tested during this project. The Academy also provided assistance by their enlisted personnel - one of whom (a Master Chief) accompanied us on tests of the 82' WPBs.

7.1.1 Fuel Additives

Dr. Sharon Zelmanowitz, from the CGA Engineering Department, enlisted some upper-class Cadets to conduct a project on fuel additives. Several commercially available additives were highly touted to improve engine performance. One had been the subject of an independent study at the University of Florida, and showed a significant drop in particulate formation with the use of a specific additive.

Preliminary to our test, we replaced our piston rings, and started with a clean engine. We also obtained some clean diesel fuel with no additives. When tested by Saybolt, Inc., the analyst said it had the best cetane rating he had ever seen.

The tests were conducted, and we found **no** improvement. Puzzled by this finding, we contacted the university professors that had conducted the tests in Florida. They said that the engine had to be run a while to build up deposits before the additive could help, i.e. no improvement could be expected with a clean engine. However, the additive in the fuel would help maintain a clean engine.

We therefore concluded that any of the commercial additives with detergent properties, would not be beneficial directly. One such additive does exist, namely cyanuric acid. In what is known as Raprenox technology, isocyanic acid is generated by thermal decomposition. It actually combines chemically with the emission products to form innocuous materials in a manner analogous to the urea/ammonia post treatment, and it is economically competitive. The problem with cyanuric acid is that it is a solid, which must be melted and injected at the proper time during the combustion to be effective. This would involve costly engine modifications.

The Department of Energy (DOE)/Martin Marietta are funding work by Texaco and the University of Wisconsin working with the Cummins Engine Co. [31-33]. They are endeavoring

to encapsulate the cyanuric acid so that it can be dispersed in the fuel, and be released at just the right time to be effective. This is still in the development stage.

7.1.2 Dual Fuel

A study was conducted on the CGA CFR engine in which natural gas was mixed with the diesel fuel, and varied from 0% up to 80% natural gas. The engine has to be started with 100% diesel, but then the natural gas can be introduced. A multivariate statistical design was made in which the amount of natural gas and compression ratio were changed, to observe the variation of NOx emissions [34, 35]. This enabled determination of the interaction of the independent variables which is not possible with an empirical approach changing the levels of one variable at a time. Five independent variables were considered: torque, speed, compression ratio, injection timing , and natural gas/ diesel fuel ratio. Emissions measured were NOx, NO, NO_2, SO , CO and CO_2, combustibles, and residual O_2. We found that injection timing should be as close to top dead center as possible, and that the benefits of using natural gas depend on engine loading. The studies showed that straight diesel fuel is best if all operations are at maximum power. The more time spent at lower powers, the greater the advantage to using some natural gas (as in harbors, and ports). Also, the compression ratio must be reduced to make the use of natural gas effective.

Five operating speeds were used. If the results are weighted equally for all five, the results appear as in Figure 7.

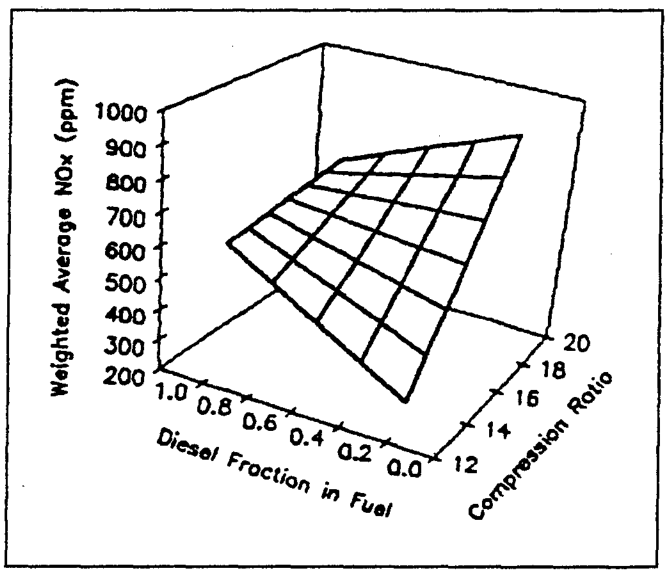


Figure 7. Effect of Fuel and Compression Ratio on NOx Emissions [35]

It is clear from Figure 7 that there is an advantage to using 80% natural gas at low compression ratios over the range of speeds studied. It must be cautioned, however that these results were

obtained using a single-cylinder CFR engine with no turbocharger. Extrapolation to larger engines may not be warranted without further studies.

7.2 MIT

We were fortunate to be able to conduct some of the research in this project at the Sloan Automotive Lab at MIT, with Coast Guard and Naval Officers in the Navy Graduate Program (see 2.2.3, p 4). Our affiliation spanned three years and seven graduate students. Much of each student's funding came from the Consortium on Lubrication in I.C. Engines. The portion relating directly to this project came jointly from the CG R&DC and MARAD. MARAD funded the last year under a National Maritime Enhancement Institute (NMEI) contract.

7.2.1 Particulates

The initial work was started using a Ricardo/Cussons standard Hydra engine connected to a dynamometer with a Digilog controller. It is a one-cylinder engine with a speed of 4500 rpm and a maximum power of 8 kW. When the Coast Guard got involved, an earlier graduate student had equipped the engine with a small dilution tunnel, which removed a sub-sample of the exhaust and passed it through a particulate filter. Thus, this engine provided the capability of determining particulates. To validate their dilution tunnel, we leased a Sierra BG-1 micro dilution tunnel for direct comparison on the same exhaust.

7.2.2 Wet Exhaust

R.B. Laurence [4], the first student, was permitted to cut into the exhaust system and insert an aqueous injector. This consisted of a concentric water injector flange, which was modeled directly from drawings of those injectors on the 82' WPBs. The purpose was to ascertain whether the water-soluble acid anhydrides (nitrogen and sulfur oxides) would end up more in the water column, rather than the air.

Saturated concentrations of nitric oxide in the water, based on solubility at the temperature of the separation tank with a known mass flow rate of water, gave the maximum removal of the oxide from the exhaust stream. However, these concentrations depend on equilibrium conditions, and the contact time was less than 5 seconds at the elevated temperature of the exhaust where the water was injected. The net result was that there was no significant reduction in nitric oxide. The maximum reduction in any of six operating conditions was 3.5% - mostly they were under 2%. The same was true for carbon monoxide and oxygen.

The next year (1995), Eric Ford [36] continued this work. Additionally, he found that an average of 8% of nitrogen dioxide reacted with the water to form nitrates.

7.2.3 Soluble Organic Fraction

Eric Ford's objective was to study effects of both oil consumption and exhaust aqueous injection on diesel engine particulate rate and gaseous emissions. He worked with Doug Schofield [28] who set up a sensitive sulfur dioxide sensor [37] to trace sulfur in the emissions to lubricating oil consumption. Schofield wrote a manual for the use of this apparatus [37]. The principle was to use "zero sulfur" sulfur fuel, so that any sulfur oxides in the exhaust are directly attributable to the lubricating oil consumed. In 1996, further assessment was made by Mark Jackson [38] of the sulfur-based diagnostic system to track lube oil consumption in the study of piston ring configurations.

Particulates were collected on filters, in the BG-1 Micro-Dilution Test Stand. Extraction with methylene chloride removed the so-called "soluble organic fraction" or SOF. This distinguishes the non-graphitic material and the organic compound. Soot *per se* is not necessarily toxic. However, many of the non-volatile organic compounds formed in the combustion process are carcinogenic (as they are in tobacco tars). We decided to conduct gas chromatography/mass spectrometry (GC/MS) on the methylene chloride extracts, and identify the organic chemical species present and their relative amounts. It was hoped that ultimately the compounds and their distribution might be correlated to the operating conditions of the engine - even perhaps be used as a diagnostic tool for combustion temperature effects, air/fuel ratio, etc. Preliminary work at the R&D Center identified 26 distinct compounds. Four of the polynuclear aromatic compounds (PNAs) were also found by ORTECH in Canada who did the GC/MS under contract for MIT. They were: phenanthrene, pyrene, fluoranthene and chrysene.

Eric Ford found that 10.5% of the soluble organics entered the water stream in the "wet exhaust." This was observed by measuring SOF on filters under both dry and wet exhaust under the same engine operating conditions.

The result of the GC/MS studies was that very likely the oily residues on the particulates are mainly from the lubricating oil consumed, and contain the carcinogenic materials. The MIT group reported [39] that an average of ~64% of the consumed lubricating oil ends up as particulate emissions. This percentage was found lowest at medium load conditions. The combination of exhaust temperature (at least 300°C) and an air-fuel ratio of about 50 at the medium load condition appears to provide an environment highly suitable for the oxidation of the consumed oil.

7.3 Penn State (PSU)

Dr. Andre' Boehman of Penn State was interested in emission products, including particulates. After hearing about our use of the BG-1 at MIT, he later became the first to have a BG-1 purchased by a university. He is in the Fuel Science Programs in the Department of Materials Science & Engineering in the College of Earth and Mineral Science. The consequence of this is that he has access to GC/MS, Fourier Transform Infrared Spectroscopy (FTIR), high performance liquid chromatography (HPLC), scanning electron microscope (SEM), and other sophisticated

analytical techniques. The Coast Guard loaned him an ENERAC 3000E to conduct tests on his research engine with and without internal ceramic coatings. We speculated that the infrared reflection from the white coating, while concentrating the heat, might still permit combustion at somewhat lower temperatures and result in lower NOx emissions. (This turned out not to be the case).

The ceramics, referred to as thermal barrier coatings (TBCs) were applied to the piston crown, the cylinder head (fire deck) and the valves of a single cylinder Yanmar TS-180 diesel utility engine with a continuous rating of 15 hp (11.2 kW) at 2400 rpm. Using spares from a second engine, it was possible to run the same engine with and without the ceramic coated parts. It was operated in ISO 8178 Mode E3 in steady state on a Clayton dynamometer. The fuel used had low sulfur and aromatics content.

In addition to collecting particulates, they determined the SOF, and then analyzed by GC, GC/MS and HPLC. Emissions were measured with the ENERAC, and an FTIR. In the uncoated engine, the normally expected results were obtained. This included particulate emission values (g/kWhr) which were highest at low load. There was also an increase in volatile (or soluble) matter content in the particulates as the speed and load are decreased. Use of the TBC-coated engine showed that the oxidation of condensable hydrocarbons is enhanced, resulting in substantially less particulate matter. The TBCs having a striking impact on the amount, morphology, and composition of particulate matter emitted from a diesel engine.

This work is summarized in Refs. [40-42].

7.4 Turbodyne

At the 1995 Diesel Engine Emission Reduction Workshop, Dr. Dorriah L Paige, of D.L. Paige Associates, Inc. presented a paper [43] on emission reductions with the Turbodyne System. The Turbodyne Systems were initially installed on automotive turbochargers, and were developed to "spin up" the turbocharger on cold startup, or acceleration in order to overcome "turbo lag" which accounts for high opacity and increased manifold pressures. Preliminary system evaluation was also conducted with several diesel engine manufacturers. (See discussion on p 6 in 2.3.5)

This seemed to offer an ideal solution for the notoriously high-emission Paxman engines on the Island Class cutters (110' WPBs). Numerous ship checks were made, an engine identified on a test block that could be tried initially. It was found that the scale was so large that the electric motors used to get up to about 30,000 rpm drew too much current. Finally, after a year of trying to get this system to the test stage, the problems appeared insurmountable, and it was dropped.

7.5 Fuel Cell Main Propulsion Systems

Fuel cells are an old technology, which only recently have offered advantages for marine propulsion. In 1994, we became aware of some breakthroughs in newly developed internally reformed direct fuel cells (DFCs), which made it feasible to test them for main propulsion [46].

The attractive feature is that they burn diesel fuel, and the only byproducts are purported to be potable water (sufficient for a third of the needs of the vessel), and carbon dioxide. They would require less manpower in the engine room, and with no moving parts in the main part of the fuel cell, would require very low maintenance (with the exception of air supply blowers, and exhaust and fuel distribution systems.

The molten carbonate fuel cells (MCFC) are the most attractive. They operate at 1000-1200°F, and have a 55% energy conversion. Four to six cells are stacked, followed by a cooling plate to conduct heat away, to a height of 8-10'. The MCFCs permit periodic cooling plates to be substituted with fuel reforming plates within the stack. This technique eliminated the need for an external fuel reformer with all its associated manifolds. It also eliminated the need for cooling plates, since the waste heat is all used for reformation. Substacks then become 1 reforming unit (RU) and 6 cells, which were called direct fuel cells (DFCs).

The glaring disadvantage for fuel cell propulsion from a logistical point of view is that they require sulfur-free fuel, since sulfur acts as a catalyst poison. This disadvantage could be overcome with the development of on-board fuel treatment for low sulfur fuels.

The test bed recommended was the T-AGOS class of vessel - primarily because it is already diesel-electric, so that all the electrical connections, electric propulsion, etc. would be in place. In addition, the Coast Guard already has this vessel class available (the Kings Pointer also would be a potential test bed).

Direct current would be available from the cells. This would require auxiliary generators, or an inverter for shipboard AC. The prototype stacks are 12' high, but could be divided into two 6' stacks with the pair conceivably putting out power comparable to a diesel occupying the same space.

The project is a multi-million dollar effort that would require interagency support. It has a high potential for payoff in direct cost savings (lower maintenance and manpower) and markedly reduced environmental impact.

The project is envisioned as a multi phase project. The first is to develop and conduct laboratory test and evaluation of a full-sized model of the DFC stack, configured as it would be aboard a ship. The subsystems of fuel service, cooling, airs supply, exhaust, containment, control, structure, etc. will be done concurrently. This would include switchboard modifications to support an AC inverter.

Among the concerns are shipboard motion, and vibration, which should be simulated on shore prior to shipboard testing. Another concern has to do with rapid changes in power demands causing a non-steady state operation. If powering down requires venting of hydrogen, then there are safety concerns that must be addressed and overcome. Shipboard testing will also expose the system to salt corrosion, temperature and humidity extremes.

The next phase would require conversion drawings for ship-specific alterations, procurement of the stacks for shipboard use, and shipyard installation. The last phase would be test and evaluation aboard the ship.

The T-AGOS has four diesel engines, and it would be possible to replace only two for the first shipboard test, so that there would be ample power available should any problems arise.

7.6 Literature Search (VNTSC) [See Appendix E for list of references]

In June 1996, the Volpe Center was tasked with a literature study of emission control technologies applicable to marine diesel engines as part of this project. It would update the extensive search made at the beginning of the project. The research effort was to focus on technologies that are most cost effective, will disrupt operations the least, and will not compromise vessel safety. The search was also to consider those technologies most likely to be adaptable to different vessel types. The eight technologies recommended were: 1. Turbo lag elimination (Turbodyne Systems, Inc.); 2. Engine upgrade kits (Fairbanks-Morse); 3. Water injection; 4. Fuel Additives (Texaco); 5. Selective non-catalytic after-treatment (Cummins Power Generation, Inc.; 6. NOx catalyst (Caterpillar); 7. NOx catalyst (Engelhard); 8. Clean diesel fuel. The preliminary search was to be followed by a survey of engine manufacturers with respect to each option, any engine specifications, rebuilt kits, fuel processors for fuel modifications, etc.

Contacts made were with various engine manufacturers (Caterpillar, EMD, Paxman), U.S. Government agencies (EPA, Navy, DOE, CG), Southwest Research Institute, Engine Manufacturer's Association, CSX, Association of American Railroads, Passenger Vessel Association, Tecogen, Allied Marine Services, Inc.

7.6.1 Selective Catalytic Reduction (SCR)

SCR is a very effective method for reducing the concentration of oxides of nitrogen in diesel engine exhausts. It uses aqueous ammonia, or urea [$(NH_2)_2CO$], which reduce the NO to nitrogen and water. The carbonyl in urea forms CO_2. Although effective, it has problems with toxicity of ammonia, bulkiness of urea and weight and size of the equipment. A locomotive application requires an estimated 4 tons of equipment. The equipment size is comparable to the engine it is controlling. Thus, it has been said that a Coast Guard cutter might have to forego its helicopter pad for the equipment, and thus compromise its mission capability. Dr. Quandt, reported [44] that the British Royal Navy is using urea for a compact design SCR for a type 23 Paxman engine. It has worked well on a test bed.

Cost estimates depend on size and configuration. An estimate by Weaver and McGregor [45] for a locomotive diesel was $350,000 capital cost, an additional $25,000 to account for modifications to the locomotive, and an estimated annual operating and maintenance cost for a line-haul locomotive application of $8.72 per kilowatt.

7.6.2 Ceramic Coatings

Ceramic coatings or thermal barrier coatings have been used extensively in the gas turbine industry for the design of engine components. Engelhard, Inc. Developed a thermal barrier coating for diesel applications called GPX Diesel-4M. It is similar to that reported in the Penn State tests of Section 7.3. There are conflicting reports about the efficacy for opacity and fuel consumption based on tests in city busses. It purports to provide easier cold start and allows the engine to come up to temperature sooner. Englehard has embarked on a test program on a single-cylinder engine. They provided cost estimates of from $1269 for DDC 6V92 engines to $6480 for EMD 16V645 for ceramic coatings.

7.6.3 Retrofits

Manufacturers have no particular incentive to retrofit engines at this time. DOE has been pressing for the manufacturer's to meet IMO/EPA specifications by the year 2000. If the new engines meet the specifications, then retrofitting becomes academic.

8.0 Summary, Conclusions, and Recommendations

8.1 Overview

This report summarizes the results of a 5-year study to ascertain the magnitude of emission problems from Coast Guard and commercial vessels, develop methodology applicable for use on small vessels by using portable emission analyzers, and examine various means of controlling emissions.

8.2 Accomplishments vs. Objectives

The major objectives were achieved. These included developing methodology for use of portable emission testers aboard any vessel (especially small ones), writing a protocol, and evaluating magnitude of emissions of various vessels.

8.2.1 Development of Methodology

Methodology had to be developed to test marine diesel exhaust emissions on small vessels. This was accomplished in this project by:

- Identifying appropriate portable emission test equipment - electrochemical sensor-based.
- Validating its use by comparison with "standard" methods - e.g. MIT direct comparison.
- Identifying the important variables - R&D Center interactive variable study.
- Developing a rigorous computational method - based on stoichiometric material balance.

8.2.2 Methodology Application

A broad spectrum of vessel types and sizes were tested for diversity, so that an omnibus protocol could be developed.

- Fourteen vessels were tested from 41' UTBs to a 600' LSD.
- Diesel engine power ranged from 500 hp to 8480 hp per engine.
- Propulsion systems included one gas turbine and one diesel-electric system.

8.2.3 Emission Ranges Tested

- NOx emissions varied from 4 to 18.7 g/kWhr.
- CO emissions varied from about 0.4 to 5.99 g/kWhr.
- SO_2 emissions varied from undetectable to 3.17 g/kWhr.

8.2.4 Protocol

A general protocol was written for the use of portable equipment on any size of vessel. It included:

- Selection of a team suitable to meet test objective.
- Writing of a test plan – including experimental design and plan for data reduction.
- Selection of test equipment – and its location on shipboard.
- Computations and reporting of data.

8.3 Other Accomplishments

A number of other aspects were examined relating to the primary objective of minimizing diesel exhaust emissions. These included:

- Development of a sound, and rigorous material balance calculation that is readily put on a computer when the appropriate data are taken.
- Dual fuel (diesel/natural gas) was examined in detail, and found to be able to reduce NOx emissions when compression ratios are lowered.
- Commercial fuel additives with detergent action merely clean dirty engines, and don't reduce emissions. Especially designed additives (e.g. cyanuric acid) show promise.
- Aqueous injection in the exhaust did not materially reduce the exhaust emissions to the air.
- Ceramic coatings (thermal barriers) in the engines materially reduced carcinogenic materials in the particulate matter of the exhaust – with little concomitant effect on NOx.
- Many of the carcinogenic materials found on particulate matter originate from the lubricating oil
- Examined in depth the potential for using fuel cells for marine propulsion systems.

8.4 Conclusions

- Portable emission testers (briefcase-sized testers with electrochemical sensors) **are** suitable for measuring emissions in the field.
- The ECOM and ENERAC give similar results to each other, and to "conventional" methods.
- Aqueous injection into the exhaust does not materially diminish the emissions.
- The most toxic portion of the particulates is in the soluble organic fraction; most of that comes from the lubricating oil, rather than the fuel.
- Most fuel additives are not effective in reducing emissions.
- Diesel-electric propulsion systems are lowest in emissions, because the diesel engines are run at constant speed.
- Breakthroughs in fuel cells have made them extremely promising for marine propulsion systems.

8.5 Significance

The primary significance of this report is that the reader can become familiar with the problems associated with shipboard testing, and learn how many of these can be overcome to obtain reasonable data on emissions from diesel engines. It discusses lessons learned and the importance of the variables in obtaining good measurements.

Information is provided to serve as a manual on how to approach shipboard testing, how to obtain necessary data, and how to perform the complex calculations required.

A broad examination is made of methods of reducing emissions including use of fuel additives, engine coatings, alternate fuels, and fuel cell propulsion.

8.6 Future Work

Suggested avenues for further work that might result in a good cost/benefit ratio are:

- Conduct a careful comparison over a significant time period of the strain gauge vs. the Stellar Marine (EMS-1000) method of measuring horsepower.
- Establish an ideal field protocol for calibration of emission equipment with minimum use of span gas (i.e. small lecture bottles).
- Compare drift stability of ENERAC 3000E and ECOM KD.
- Evaluate the fuel-saving potential of the ESP-1000 in a prolonged test,
- Stay abreast of developments of the cyanuric acid encapsulated additive, and its potential for large-scale use.
- Examine means of reducing particulates, and particularly the carcinogens that accompany them.
- Continue pushing for full-scale ship test of fuel cells in diesel-electric propulsion.
- Look for efficient means of desulfurizing diesel fuel.

9.0 References

[1] "U.S. Coast Guard/U.S. Maritime Administration Cooperative Research on Marine Engine Exhaust Emissions - Marine Exhaust Emissions Measurement of the M/V Kings Pointer" by S.J. Allen and A.P. Bentz, U.S. Coast Guard Research & Development Center Report No. CG-D-1496 (July 1996)

[2] "Marine Exhaust Emissions Research Programme," Lloyd's Register of Shipping
a. Medium Speed Engines - Steady State Operation (1990)
b. Slow Speed Addendum (1990)
c. Phase II Summary Report (1993)
d. Marine Exhaust Emissions Programme [final report on completion of program](1995)

[3] ISO 8178
a. Part 4: "Test Cycles for Different Engine Applications" (1992), Section 6.5, "Test Cycles Type E, Marine Applications."
b. Part 1: RIC Engines - Exhaust Emission Measurement" (1992), Section 11, "Particulate Measurement. "
c. Part 1: ibid. Section 13, "Calculation of the gaseous emissions."
d Part 1: " Annex D.

[4] "The Effect of Lubrication System and Marine-Specific Factors on Diesel Engine Emissions" by Ronald B. Laurence Jr., MIT Thesis (1994).

[5] "U.S. Coast Guard/U.S. Maritime Administration Cooperative Research on Marine Engine Exhaust Emissions - Experimental Design on Marine Exhaust Emissions," by M.J. Goodwin, U.S. Coast Guard Research and Development Center Report No. CG-D-08-95 (January 1995), NTIS Accession No. AD-A2936603.

[6] "Air Data Multimeter ADM-870 Electronic Microanemometer", Technical Manual, Shortridge Instruments, Inc. Scottsdale, AZ.

[7] "Description, Operation, Installation and Maintenance Instruction for Propulsion Shaft Horsepower Measurement Systems," Technical Manual, Model Series 1642A, Accurex Corp., Autodata Division (now Wireless Data Corporation), Mountain View CA.

[8] "EMS-1000 Fuel Management System Manual," by Stellar Marine, a Division of Stellar Research Corporation..

[9] Bob Speed (President of Stellar Marine), Private Communication (2/97).

[10] "Shipboard Marine Engines Emissions Testing for the United States Coast Guard," Delivery Order 31, Final Report (1995), by Environmental Transportation Consultants.

[11] "ECOM-KD Manual," Technical Manual, ECOM AMERICA, 3075 Breckenridge Blvd., Suite 420, Duluth, GA 30136.

[12] "ENERAC 3000E Compliance-Level Emission Analyzers Instruction Manual," Energy Efficiency Systems, Inc., 1300 Shanes Drive, Westbury, NY 11590.

[13] "Emission Regulations for New Diesel Heavy Duty Engines - Gaseous Exhaust Test Procedures," CFR Part 86-79, Subpart D (1979).

[14] "Stationary Internal Combustion Engines; Standards of Performance for New Stationary Sources," U.S. Federal Register, Vol. *44*, No. 142 (1979).

[15] "EPA's Conditional Test Method (CT-022), A scientifically Sound Framework for the Use of NOx Electrochemical Sensors," Energy Efficiency Systems, Inc. March 1996, (unpublished).

[16] Todd Sherwood, US EPA, National Vehicle and Fuels Emission Laboratory, Ann Arbor MI, Private Communication (3/14/95).

[17] "Marine Diesel Exhaust Emissions Measured by Portable Instruments," by Alan P. Bentz and Elizabeth Weaver, SAE Technical Paper 941784 - Presented at the International Off-Highway Congress in Milwaukee WI on September 1994.

[18] "Technical Evaluation of the CG-47201 6V-92 Detroit Diesel Electronic Control (DDEC) Propulsion Modification, Robert Lattas, USCG R&DC, January 1995

[19} "Exhaust Emission Testing - 47' Motor Lifeboat (MLB) [CG-47201]," by Alan P. Bentz, US Coast Guard R&D Center internal report June 1996.

[20] "Determination of Naval Medium Speed Diesel Engine Air Exhaust Emissions, and Validation of a Proposed Estimation Model," by Agnes Mayeaux, MIT Thesis (1995).

[21] "Marine Exhaust Emissions Measurement of the M/V KINGS POINTER" by S. J. Allen and A. P. Bentz, USCG Report No. CG-D-1496, July 1996.

[22] "Portable Emissions Testing of a 105-Ft Commercial Tug," by Alan Bentz, Bert Macesker and Robert Desruisseau, Report No. CG-D-07-97. NTIS Accession No. AD-A32-3569, October 1996.

[23] "Portable Emissions Testing of Construction Tender KENNEBEC (WLIC-160)" by Alan Bentz, Final Report to Volpe National Transportation Systems Center, June 1997.

[24] 'Steam, Its Generation and Use" by The Babcock and Wilcox Co., 37th Ed pp4-8 and 4-A5 and 4-A6 (1955); 40th Ed, Editors Steven C. Stutz and John B. Kitto, p 907 (1972).

[25] "Development of Naval Diesel Engine Duty Cycles for Air Exhaust Emission Environmental Impact Analysis," by Stephen Paul Markle, MIT Thesis (1994).

[26] " Guidelines Part A for Implementation of NOx Limits for Marine Diesel Engines, 2. Actual Limits" IMO Sub -Committee on Bulk Chemicals (BCH 24/7/6, Annex 2,Reg. 12).

[27] "Reference Method 40 CFR 60, Appendix A, Method 7E."

[28] "Diesel Engine Instantaneous Oil Consumption Measurements Using the Sulfur Dioxide Tracer Technique," by Douglas M. Schofield, MIT Thesis (1995).

[29] "Assessment of a Sulfur Dioxide-Based Diagnostic System in Characterizing Real-Time Oil Consumption in a Diesel Engine," by Mark A. Jackson, MIT Thesis (1996).

[30] "Particle pollution taking stage; tiny airborne bits viewed as big killer," New York Times News Service, dateline Washington DC, 19 July 1993.

[31] "Overview - Chemical Additive to Reduce NOx in Diesel Engines", by David E. Foster, 1993 Diesel Engine Emissions Reduction Workshop, DOE, La Jolla CA (1993).

[32] "NOx Emission Reducing Fuel Additive", by Benjamin J. Kaufman, Iftkhar Alam, Thomas F. DeRosa, and Joseph M. Russo, 1995 Diesel Engine Emissions Reduction Workshop, DOE, La Jolla CA (1995).

[33] "Progress in Diesel Exhaust NOx Reduction Through the Use of Fuel Additives," by David E. Foster, 1995 Diesel Engine Emissions Reduction Workshop, DOE, La Jolla CA (1995).

[34] "Overview of US Coast Guard and US Maritime Administration Project on Marine Exhaust Emissions, and Alternate Fuels," 1995 Diesel Engine Emissions Reduction Workshop, DOE, La Jolla CA (1995).

[35] "Multivariate Emission Experiment with a Dual-Fueled CFR Engine," by Alan P. Bentz, Michael J. Goodwin, and Timothy J. Killeen, ICE Vol. 25-1, Proceedings of the 17th Annual Fall Technical Conference of The ASME Internal Combustion Engine Division (1995).

[36] "The Effects of Lubrication System Parameters and Exhaust Aqueous Injection on Diesel Engine Oil Consumption and Emissions" by Eric J. Ford, MIT Thesis (1995).

[37] "Installation and Operation of a Sulfur Dioxide Tracing Real-Time Oil Consumption Apparatus" by Doug Schofield with guidance from Richard Flaherty of Cummins Engine Company (1995). This is a manual prepared for future operation at MIT.

[38] "Characterization of Lube Oil-Derived Diesel Engine Particulate Emission Rate vs. Lube Oil Consumption" by Thomas C. Miller

[39] "Prevention of Air Pollution From Ships: Characterization and Assessment of Diesel Particulate Emission Reduction via Lube-Oil-Consumption Control" by Victor W. Wong, Alan J. Brown of MIT, Final Report for Maritime Administration Contract DTMA91-95-H-0051 for period 4/1/95-7/31/96, Report No. MA-ENV-820-96004 (March 1997).

[40] "The Influence of Thermal Barrier Coatings on Diesel Engine Emissions" by Manohar Vittal, Jeffrey Borek, Debra A. Marks, and Andre' L. Boehman. Topical Report 1 (Nov 1996).

[41] "The Influence of Thermal Barrier Coatings on Morphology and Composition of Diesel Particulates" by Debra A. Marks and Andre' L. Boehman, SAE Paper No. 970756, presented at SAE Congress (Feb 1997).

[42] "The Effects of Thermal Barrier Coatings on Diesel Engine Emissions" by A. L. Boehman, M. Vittal, J.A. Borek, D.A. Marks and A.P. Bentz, American Society of Mechanical Engineers Fall Technical Conference, Madison WI (30 Sept. 1997).

[43] "Emissions Reduction and Improved Engine performance with the Turbodyne System" by Dorriah L. Page, 1995 Diesel Engine Emissions Reduction Workshop, sponsored by DOE Office of Transportation Technologies (July 1995).

[44] "European Technology for Reducing Exhaust Pollution from Naval Ship Engines," Earl Quandt, Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-80-96/02 (April 1996).

[45] "Emission Control Technology for Locomotive Engines," SAE Paper No. 940453, by Christopher S. Weaver and Douglas B. McGregor. Diesel Exhaust Aftertreatment 1994, SP-1020, SAE International, Warrendale PA (Feb 1994).

[46] "Marine Application of Fuel Cells," by Arctic Energies LTD (AEL), under NOAA Contract No. 50-DGNA-4-00037 to Resource Consultant, Inc., Subcontract No. 1000-03859 to AEL (April 1994).

APPENDIX A

MODEL CALCULATIONS - R&D CENTER

SAMPLE EMISSION CALCULATION
OF NOx EMISSIONS FOR KENNEBEC

Calculations are based on a stoichiometric material balance of incoming fuel and air with exhaust. The basic assumption is that there is more than sufficient oxygen available in the air entering the diesel engine to effect complete combustion of the fuel components. For the material balance, the quantity of air per unit time (including water vapor), and the quantity of fuel per unit time account for all incoming materials. This represents the mass in the exhaust; the products are determined by the reaction stoichiometry, and the analysis of the concentrations of products in the exhaust.

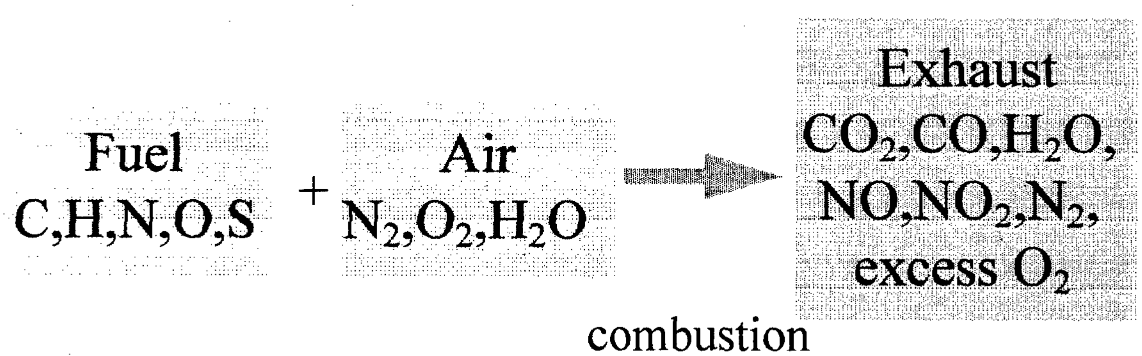
Laboratory analysis of the fuel quantitatively measures the elemental components of the fuel. Theoretical amounts of combustion products (assuming complete combustion) are computed using the equations below:

$$C + O_2 = CO_2 \qquad S + O_2 = SO_2$$
$$4H + O_2 = 2H_2O \qquad N + O_2 = NO_2$$

These equations permit calculation of the theoretical amount of oxygen required (and therefore air) for complete combustion. Any air above that amount is "excess air." In actuality, complete stoichiometric combustion does not occur. Thus, not all carbon is completely converted to CO_2. However, once the CO is experimentally determined, the actual CO_2 can be calculated. Similarly, not all nitrogen goes to NO_2, but the NO formed is independently measured.

Water is the product of combustion of hydrogen, but there is also water in the exhaust that entered as water vapor in the air. This source of water requires no additional oxygen, but must be accounted for in the total material balance. Any oxygen in the fuel (as oxygen-containing compounds) must be subtracted from the total oxygen required, since it contributes to the oxygen available.

Sulfur in the fuel produces SO_2. Overall, the material balance is given schematically as follows:



By tracking the substances and their amounts, it is possible to compute the amounts expected in the exhaust of primary combustion products. Analysis of the exhaust for CO, NO, NO_2, and SO_2, permits complete material balance.

Table A1 presents the fuel analysis in the first two columns. The fuel analysis of samples of the Tug COUGAR's fuel was performed by Saybolt, Inc. Using the equations described previously, with the appropriate atomic weights, the moles of oxygen needed can be calculated.

Table A1
Calculated Oxygen Requirement for Complete Combustion Based on Fuel Analysis

Fuel Comp	lb/100lb fuel[a]	MWT of Comp	Moles of Comp	Moles 02 req
C	86.85	12.011	7.231	7.231
H	13.02	1.008	12.917	3.233[b]
S	0.30	32.060	0.00935	0.009
O	0.020	16.000	-0.001	-0.001
N	0.22	14.007	0.016	0.016
H20	0.05	18.016	0.90	0.000
Ash	<0.001			
Total	100.46			10.488

[a] based on fuel analysis
[b] represents 6.466 moles of water

From the information above (temperature, pressure, and humidity of the incoming air), the goal is to calculate the moles of dry flue gas (DFG) generated per unit time. Although, the exiting gas is wet, the instruments used for measuring the combustion products must first dry the air to protect the electrochemical sensors. Thus, the concentration of NOx in ppm, for example, is based on the amount found in the DFG.

The following example calculations are performed for the data collected on the port Caterpillar engine at full speed without the speed pilot engaged. The calculation is shown for a test rpm of 1237. Computations below are based on data taken on 12 November 1996 on the Inland Construction Tender Kennebec (WLIC-160) No. 802.

Density of Wet Air

$$\rho(\text{wet air})[\text{lb/ft}^3] = \frac{1.326 \times \text{Pres}}{459.6 + \text{F}} \qquad [1]$$

Air entering the engines had an average temperature of 91.5 °F and measured an average atmospheric pressure of 30.7 in Hg, thus,

$$= \frac{1.326 \times 30.7}{459.6 + 91.5} = 0.0738 \text{ lb/ft}^3 \qquad [2]$$

Air Flow wet [lb/min]

= [2] x CFM(meas)
= 0.0738 lb/ft^3 x 1010 ft^3/min
= 74.5 lb/min [3]

Fuel Flow [gal/min]

= 28.93 GPH(meas) x 1 hr/60 min
= 0.482 gal/min [4]

Fuel Consumed [lb/min]

density of standard diesel approx. 7.09 lb/gal [5]
= 7.09 lb/gal(ρ_{diesel}) x [4]
= 3.43 lb/min [6]

Air / Fuel Ratio wet [lb/100lb]

= [3] / [6]
= 103.63 lb/min / 3.67 lb/min = 21.70 lb A/lb F
Or = 2170 lb/100lb [7]

Air Flow dry [lb/min]

= Air Flow wet - (Air Flow wet x RHc),

where RHc is the humidity correction value from the pschrometric chart with measured temperature of 91.5 °F (33.1 °C) and measured averaged relative humidity of 12%,

= [3] - ([3] x 0.005) = 74.5 - (74.5 x 0.003)
= 74.3 lb/min [8]

Air / Fuel Ratio dry [lb/100lb]

= [8] / [6]
= 74.3 lb/min / 3.43 lb/min = 21.64 lb A/100 lb F
= 2164 lb/100lb [9]

The next step is to determine the total oxygen and nitrogen available for combustion in the incoming air, where the weight % of oxygen is 23.14% and that of nitrogen is 76.86%.

Total O_2 [lb O_2 / 100 lb Fuel]

= [9] x 0.2314 lb O_2/lb air
= 2164 lb/100lb x 0.2314 lb O_2/lb air
= 501 lb/100lb [10]

Total N_2 [lb N_2 / 100 lb Fuel]

= [9] x 0.7686 lb O2/lb air
= 2164 lb/100lb x 0.7686 lb O2/lb air
= 1663 lb/100lb [11]

Moles of O_2 Theoretically Required [moles O_2 / 100 lb Fuel]

= 10.488 moles/100lb [12]
(from fuel composition in Table A1)

Excess Air [lb air/100 lb fuel]

= Actual Air in - Theoretical Air In

$$= [9] - [12] \times \frac{32 \text{ lb } O_2}{1 \text{ mole } O_2} \times \frac{1 \text{ lb air}}{0.2314 \text{ lb } O_2}$$

= 2164 lb/100lb - 1451 lb/100lb
= 713 lb/100lb [13]

Percent Excess Air [%]

= Excess Air / Theoretical Air in
= 713 lb/100lb / 1451 lb/100lb x 100
= 49% [14]

Excess O_2 [moles O_2/100lb Fuel]

$$= [13] \times \frac{0.2314 \text{ lb } O_2}{1 \text{ lb air}} \times \frac{1 \text{ mole } O_2}{32 \text{ lb } O_2}$$

= 5.2 moles/100lb [15]

Water in Air [moles H_2O/100 lb Fuel]

= [7] x lb H_2O/lb air (from Pschrometric Chart)

$$= 2170 \text{ lb air/100lb Fuel} \times 0.003 \text{ lb } H_2O\text{/lb air} \times \frac{1 \text{ mole } H_2O}{18 \text{ lb } H_2O}$$

= 0.36 moles H_2O/100lb [16]

$CO_2 + SO_2$ [moles (CO_2+SO_2) / 100lb Fuel]

= 7.231 + 0.009 (from Table A1)
= 7.240 moles/100lb [17]

O_2 Supplied [moles O_2/100lb Fuel]

$$= [10] \times \frac{1 \text{ mole } O_2}{32 \text{ lb } O_2} = 501/32$$
= 15.65 moles/100lb [18]

N_2 Supplied [moles N_2/100lb Fuel]

$$= [11] \times \frac{1 \text{ mole } N_2}{28.161 \text{ lb } N_2} = 1663/28.161$$
= 59.06 moles/100lb [19]

H_2O Total [moles H_2O/100lb Fuel]

= [16] + moles combustion product

(where the combustion product is from HCs and equal to 0.06466 moles H_2O/lb Fuel)
= 0.36 moles H_2O/100lb Fuel +
6.50 moles H_2O/100lb Fuel
= 6.86moles/100lb [20]
or = 123.5 lb H_2O/100lb Fuel [21]

Total Moles of Wet Flue Gas [moles WFG/100lb Fuel]

= (CO_2 + SO_2) + excess O_2 + N_2 + H_2O
= [17] + [15] + [19] + [20]
= 7.2 moles/100lb + 5.2 moles/100lb + 59.0 moles/100lb
+ 6.9 moles/100lb
= 78.3 moles/100lb [22]

Total Moles of Dry Flue Gas [moles DFG/100lb Fuel]

= moles WFG - moles H_2O = [22] - [20]
= 78.3 moles/100lb - 6.9 moles/100lb
= 71.4 moles/100lb [23]

Moles CO [moles CO/100lb Fuel]

= CO ppm x [23]
= $294 \times 10^{-6} \times 71.4$ moles/100lb

$= 0.021$ moles/100lb [24]

Moles NO [moles NO/100lb Fuel]

$= NO$ ppm x [23]
$= 1126$ ppm x 10^{-6} x 71.4 moles/100lb
$= 0.0805$ moles/100lb [25]

Moles NO_2 [moles NO_2/100lb Fuel]

$= NO_2$ ppm x [23]
$= 11.5 \times 10^{-6} \times 71.4$ moles/100lb
$= 0.00082$ moles/100lb [26]

Moles SO_2 [moles SO_2/100lb Fuel]

$= SO_2$ ppm x [23] $= 45 \times 10^{-6} \times 71.4$ moles/100 lb
$= 0.0032$ moles/100lb [27]

Moles CO_2 [moles CO_2/100lb Fuel]

= moles CO_2 (theoretical) - moles CO (actual [24])
$= 7.231 - 0.021$
$= 7.21$ moles/100lb [28]

from CO_2 measurement on emission analyzer 8.6% CO_2
$= 0.086$ x [23]
$= 0.086 \times 71.4$ moles/100lb
$= 6.14$ moles/100lb [28A]

Weight of NO [lb NO/100lb Fuel]

= [25] x 30.008 lb NO/mole
$= 0.0805$ moles/100lb x 30.008 lb NO/mole
$= 2.41$ lb/100lb [29]

Weight of NO_2 [lb NO2/100lb Fuel]

= [26] x 46.007 lb NO_2/mole
$= 0.00082$ moles/100lb x 46.007 lb NO_2/mole
$= 0.038$ lb/100lb [30]

Weight of SO_2 [lb SO_2/100lb Fuel]

= [27] x 64.12 = 0.0032 X 64.12
$= 0.21$ lb SO_2/100lb fuel [31]

Weight of CO_2 [lb CO2/100lb Fuel]

= [28] x 44.011 lb CO_2/mole
= 7.21 moles/100lb x 44.011 lb CO_2/mole
= 317.3 lb/100lb [32]

NOx Weight [lb NOx/100lb Fuel]

= [29] + [30]
= 2.41 lb/100lb + 0.038 lb/100lb
= 2.448 lb/100lb [33]

Fuel Consumed in 1 hour [lb]

= [6] x 60 min/hr
= 3.43 lb/min x 60 min/hr
= 205.8 lb [34]

Work done in 1 hour [kWhr]

= shaft HP x 0.746 kW/HP = 493 x 0.746
= 367.8 kWhr [35]

Fuel Consumed/kWhr = 205.8/367.8 = 0.560 lb/kWhr [36]

NOx Produced in 1 hour [grams NOx/hour]

= [33]/100 x [34]
= 2.448 lb/100lb /100 x 205.8 lb
= 5.04 lb NOx/hr
= 5.04 lb NOx/hr x 453.4g/lb = 2284 g/hr [37]

NOx [g/kWh]

= [37] / [36]
= 2284 g/hr / 367.8 kWhr
= 6.21 g/kWhr [38]

(CO in g/kWh is calculated in the same fashion)

NOx [kg/tonne of Fuel]

= [33] x 10
= 2.448 lb/100lb x 10
= 24.48 kg/tonne of Fuel [39]

APPENDIX B

EMISSION CALCULATIONS FROM ISO 8178-1

12 Data evaluation for gaseous and particulate emissions

12.1 Gaseous emissions

For the evaluation of the gaseous emissions, the chart reading of the last 60 seconds of each mode shall be averaged, and the average concentrations (conc) of HC, CO, CO_2, NO_x, O_2, NMHC (NMC method), NH_3, and CH_3OH (FID method) during each mode shall be determined from the average chart readings and the corresponding calibration data. A different type of recording can be used if it ensures an equivalent data acquisition.

The average background concentrations ($conc_d$) shall be determined from the bag readings of the dilution air or from the averaged continuous (non bag) background reading and the corresponding calibration data.

When using impinger or cartridge sampling methods for HCHO and CH_3OH, the concentrations (conc) and background concentrations ($conc_d$, if used) shall be determined from the HCHO/CH_3OH masses in the impingers (cartridges) as desribed in Clauses 15.4 and 15.5 and the total sample masses through the impingers (cartridges).

12.2 Particulate emissions

For the evaluation of the particulates, the total sample masses through the filters ($M_{SAM,i}$) and the dilution ratios (q_i) for each mode shall be recorded.

The filters shall be returned to the weighing chamber and conditioned for at least two hours, but not more than 80 hours, and then weighed. The gross weight of the filters shall be recorded. The particulate mass (P_f) is the sum of the particulate masses collected on the primary and back-up filters.

13 Calculation of the gaseous emissions

The finally reported test results shall be derived through the following steps:

13.1 Determination of the exhaust gas flow

The exhaust gas flow rate (G_{EXHW}, V_{EXHW}, or V_{EXHD}) shall be determined for each mode according to Clauses 7.2.1 to 7.2.3.

When using a full flow dilution system, the total dilute exhaust gas flow rate (G_{TOTW}, V_{TOTW}) shall be determined for each mode according to clause 7.2.4.

13.2 Dry / wet correction

When applying G_{EXHW}, V_{EXHW}, G_{TOTW}, or V_{TOTW}, the measured concentration shall be converted to a wet basis according to the following formulae, if not already measured on a wet basis.

$$conc(wet) = K_W * conc(dry) \quad (12)$$

For the raw exhaust gas:

$$K_{W,r} = \left(1 - F_{FH} * \frac{G_{FUEL}}{G_{AIRD}}\right) - K_{W2} \quad (13)$$

or $$K_{W,r} = (1/(1 + F_{FH} * 0{,}005 * (\% CO + \% CO2))) - K_{W2} \quad (14)$$

For the diluted exhaust gas:

$$K_{W,e} = \left(1 - \frac{F_{FH} * CO_2\%(wet)}{200}\right) - K_{W1} \quad (15)$$

or

$$K_{W,e} = \left(\frac{(1 - K_{W1})}{1 + \frac{F_{FH} * CO_2\%(dry)}{200}}\right) \quad (16)$$

Values for F_{FH} see ISO 8178-5 (under consideration)

For the dilution air

$$K_{W,d} = 1 - K_{W1} \quad (17)$$

$$K_{W1} = (1{,}608 * H_d)/(1000 + H_d) \quad (18)$$

$$H_d = \frac{6{,}220 * R_d * p_d}{p_B - p_d * R_d * 10^{-2}} \quad (19)$$

For the intake air (if different from the dilution air)

$$K_{W,a} = 1 - K_{W2} \quad (20)$$

$$K_{W2} = (1{,}608 * H_a)/(1000 + H_a) \quad (21)$$

$$H_a = \frac{6{,}220 * R_a * p_a}{p_B - p_a * R_a * 10^{-2}} \quad (22)$$

H_a, H_d : g water per kg dry air

R_d = relative humidity of the dilution air, %
R_a = relative humidity of the intake air, %
p_d = saturation vapour pressure of the dilution air, kPa
p_a = saturation vapour pressure of the intake air, kPa
p_B = total barometric pressure, kPa

13.3 Humidity correction for NO_x

As the NO_x emission depends on ambient air conditions, the NO_x concentration shall be corrected for ambient air temperature and humidity with the factors K_H given in the following formulae.

For engines operating on alternative combustion cycles other correction formulas may be used if they can be justified or validated.

a) for diesel engines:

$$K_{HDIES} = \frac{1}{1 + A^{*}(H_a - 10{,}71) + B^{*}(T_a - 302{,}6)} \qquad (23)$$

with:

A = $0.309\ G_{Fuel}/G_{AIRD} - 0.0266$
B = $-0.209\ G_{Fuel}/G_{AIRD} + 0.00954$
T = temperature of the air in K

$\frac{G_{FUEL}}{G_{AIRD}}$ = Fuel air ratio (dry air basis)

H_a = humidity of the intake air,g water per kg dry air

in which

$$H_a = \frac{6{,}220^{*} R_a^{*} p_a}{p_B - p_a^{*} R_a^{*} 10^{-2}}$$

R_a = relative humidity of the intake air, %
p_a = saturation vapour pressure of the intake air, kPa
p_B = total barometric pressure, kPa

b) for diesel engines with intermediate air cooler the following alternative equation may be used:

$$K_{HDIES} = \frac{1}{1 - 0{,}012^{*}(H_a - 10{,}71) - 0{,}00275^{*}(T_a - 302{,}6) + 0{,}00285^{*}(T_{SC} - T_{SC\ Ref})} \qquad (24)$$

T_{SCRef} : To be specified by the manufacturer
(explanation of the variables see under a))

c) for gasoline engines:

$$K_{HPET} = 0{,}6272 + 44{,}030 \cdot 10^{-3} \cdot H - 0{,}862 \cdot 10^{-3} \cdot H^2 \qquad (25)$$

(explanation of the variables see under a))

13.4 Calculation of emission mass flow rates

The emission mass flow rates for each mode shall be calculated as follows:

a) For the raw exhaust gas:

$$\text{Gas mass} = u * conc * G_{EXHW} \quad (26)$$

or

$$\text{Gas mass} = v * conc * V_{EXHD} \quad (27)$$

or

$$\text{Gas mass} = w * conc * V_{EXHW} \quad (28)$$

b) For the dilute exhaust gas:

$$\text{Gas mass} = u * conc_c * G_{TOTW} \quad (29)$$

or

$$\text{Gas mass} = w * conc_c * V_{TOTW} \quad (30)$$

where

$conc_c$ is the background corrected concentration

$$conc_c = conc - conc_d * (1 - (1/DF)) \quad (31)$$

$$DF = 13{,}4/(concCO_2 + (concCO + concHC)*10^{-4})) \quad (32)$$

or

$$DF = 13{,}4/concCO_2 \quad (33)$$

The coefficients u - wet, v - dry, w - wet shall be used according to table 8:

Table 8- Coefficients u , v , w.

Gas	u	v	w	conc.
NO_X	0,001587	0,002053	0,002053	ppm
CO	0,000966	0,00125	0,00125	ppm
HC	0,000479	-	0,000619	ppm
CO_2	15,19	19,64	19,64	percent
O_2	11,05	14,29	14,29	percent
NH_3	0,000597	0,000771	0,000771	ppm
CH_4	0,000555	0,000717	0,000717	ppm
HCHO	0,001037	0,001341	0,001341	ppm
CH_3OH	0,001106	0,001430	0,001430	ppm
	NMC cutter method see annex C			ppm

Note:
The given coefficients u,v,w are calculated for 273,15 K (0°C) and 101,3 kPa (see annex D). In cases, where the total allowed range of the reference conditions according to clause 5.2 is used, an error of 2 % is possible.

The density of HC is based upon an average carbon to hydrogen ratio of 1 / 1,85.

13.5 Calculation of the specific emissions

The emission shall be calculated for all individual components in the following way:

$$\text{individual gas} = \frac{\sum_{i=1}^{i=n} \text{Gas mass}_i * WF_i}{\sum_{i=1}^{i=n} p_i * WF_i} \quad (34)$$

where $P_i = P_{M,i} + P_{AUX,i}$ (35)

The weighting factors and the number of modes(n) used in the above calculation are according to the provisions of ISO 8178-4.

14 Calculation of the particulate emission

The particulate emission shall be calculated in the following way:

14.1 Humidity correction factor for particulates

As the particulate emission of Diesel engines depends on ambient air conditions, the particulate concentration shall be corrected for ambient air humidity with the factor K_p given in the following formulae.

For engines running on other than light distillate fuels (see Part 5) other correction formulae may be used if they can be justified or validated.

$$K_p = 1/(1 + 0{,}0133 * (H_a - 10{,}71)) \quad (36)$$

H_a = humidity of the intake air, g water per kg dry air

$$H_a = (6{,}220 * R_a * p_a)/(p_B - p_a * R_a * 10^{-2}) \quad (37)$$

R_a = relative humidity of the intake air, %

p_a = saturation vapour pressure of the intake air, kPa

p_B = total barometric pressure, kPa

14.2 Partial flow dilution system

The final reported test results of the particulate emission shall be derived through the following steps. Since various types of dilution rate control may be used, different calculation methods for G_{EDFW} or V_{EDFW} apply. All calculations shall be based upon the average values of the individual modes during the sampling period.

14.2.1 Isokinetic systems

See clause 16.1.1 (Figures 10,11)

$$G_{EDFW,i} = G_{EXHW,i} * q_i \quad (38)$$

or

$$V_{EDFW,i} = V_{EXHW,i} * q_i \quad (39)$$

$$q_i = \frac{G_{DILW,i}+(G_{EXHW,i}*r)}{(G_{EXHW,i}*r)} \quad (40)$$

or

$$q_i = \frac{V_{DILW,i}+(V_{EXHW,i}*r)}{(V_{EXHW,i}*r)} \quad (41)$$

where r corresponds to the ratio of the cross sectional areas of the isokinetic probe and the exhaust pipe:

$$r = \frac{A_p}{A_T} \quad (42)$$

14.2.2 Systems with measurement of CO_2 or NO_x concentration

See clause 16.1.1, (Figures 12, 14, 15, 16)

$$G_{EDFW,i} = G_{EXHW,i} * q_i \tag{43}$$

or

$$V_{EDFW,i} = V_{EXHW,i} * q_i \tag{44}$$

$$q_i = \frac{Conc_{E,i} - Conc_{A,i}}{Conc_{D,i} - Conc_{A,i}} \tag{45}$$

where

$Conc_E$ = wet concentration of the tracer gas in raw exhaust
$Conc_D$ = wet concentration of the tracer gas in the diluted exhaust
$Conc_A$ = wet concentration of the tracer gas in the dilution air

Concentrations measured on a dry basis shall be converted to a wet basis according to clause 13.2.

14.2.3 Systems with CO_2 measurement and carbon balance method

See clause 16.1.1 (Figure 13)

$$G_{EDF,i} = \frac{F_{FCB} * G_{FUEL,i}}{CO_{2D,i} - CO_{2A,i}} \tag{46}$$

where

CO_{2D} = CO_2 concentration of the diluted exhaust

CO_{2A} = CO_2 concentration of the dilution air

(concentrations in Vol % on wet basis)

Values for F_{FCB} see table 9. The calculation of F_{FCB} from other fuels see ISO 8178-5 annex A

This equation is based upon the carbon balance assumption (carbon atoms supplied to the engine are emitted as CO_2) and derived through the following steps:

$$G_{EDF,i} = G_{EXHW,i} * q_i \tag{47}$$

and

$$q_i = \frac{F_{FCB} * G_{FUEL,i}}{G_{EXHW,i} * (CO_{2D,i} - CO_{2A,i})} \tag{48}$$

Table 9 - F_{FCB} and other parameters for some selected fuels (examples)

Fuel	C%	H%	S%	O%	λ	FFH	FFW	FFD	FFCB	EXH DENS
DIESEL	86,2	13,6	0,17	0,0	1 1,35 4,35	1,783 1,865 1,920	0,749	-0,767	206,6	1,295 1,296 1,292
RME	76,8	11,0	0,0	12,1	1 1,35 4,35	1,478 1,503 1,548	0,688	-0,535	184,1	1,305 1,299 1,294
Methanole	37,8	12,8	0,0	49,0	1 1,35 4,35	1,605 1,653 1,755	1,045	-0,354	89,8	1,254 1,263 1,282
Ethanole	52,1	13,1	0,0	34,7	1 1,35 4,35	1,706 1,748 1,840	0,967	-0,492	125	1,267 1,273 1,285
Nat.Gas	76	24	0	0	1 1,35 4,35	3,128 3,203 3,347	1,326	-1,341	182,1	1,242 1,252 1,272
Propane	81,7	18,3	0	0	1 1,35 4,35	2,423 2,471 2,574	1,007	-1,025	195,8	1,268 1,274 1,286
Butane	82,7	17,3	0	0	1 1,35 4,35	2,304 2,348 2,444	0,955	-0,972	198,1	1,273 1,278 1,287

14.2.4 Systems with flow measurement

See clause 16.1.1 (Figures 17, 18)

$$G_{EDF,i} = G_{EXHW,i} * q_i \qquad (49)$$

$$q_i = \frac{G_{TOTW,i}}{(G_{TOTW,i} - G_{DILW,i})} \qquad (50)$$

14.3 Full flow dilution system

The final reported test results of the particulate emission shall be derived through the following steps.

All calculations shall be based upon the average values of the individual modes during the sampling period.

$$G_{EDFW,i} = G_{TOTW,i} \tag{51}$$

or

$$V_{EDFW,i} = V_{TOTW,i} \tag{52}$$

14.4 Calculation of the particulate mass flow rate

The particulate mass flow rate shall be calculated as follows:

for the single filter method

$$PT_{MASS} = \frac{P_f * (G_{EDF})^{aver}}{M_{SAM} * 1000} \quad (53)$$

or

$$PT_{MASS} = \frac{P_f * (V_{EDFW})^{aver}}{V_{SAM} * 1000} \quad (54)$$

PT mass,i corrected (dilution air) (55)
to be added later
where

$(G_{EDF})^{aver}$,
$(V_{EDF})^{aver}$
$(M_{SAM})^{aver}$, and $(V_{SAM})^{aver}$

over the test cycle shall be determined by summation of the average values of the individual modes during the sampling period:

$$(G_{EDF})^{aver} = \sum_{i=1}^{i=n} G_{EDF,i} * WF_i \quad (56)$$

$$(V_{EDF})^{aver} = \sum_{i=1}^{i=n} V_{EDFW,i} * WF_i \quad (57)$$

$$M_{SAM} = \sum_{i=1}^{i=n} M_{SAM,i} \quad (58)$$

$$V_{SAM} = \sum_{i=1}^{i=n} V_{SAM,i} \quad (59)$$

$i = 1, \ldots, n$

for the multiple filter method

$$PT_{MASS,i} = \frac{P_{f,i} * (G_{EDF,i})}{M_{SAM,i} * 1000} \quad (60)$$

or

$$PT_{MASS,i} = \frac{P_{f,i} * (V_{EDFW,i})}{V_{SAM,i} * 1000} \quad (61)$$

PT mass,i corrected (dilution air) (62)
to be added later

$i = 1, \ldots, n$

14.5 Calculation of the specific emissions

The particulate emission shall be calculated in the following way

for the single filter method

$$(PT)_{aver} = \frac{PT_{MASS}}{\sum_{i=1}^{i=n} P_i * WF_i} \qquad (63)$$

for the mult

$$(PT)_{aver} = $$

14.6 Effective weighting factor

For the single filter method, the effective weighting factor $WF_{E,i}$ 1
in the following way:

$$WF_{E,i} = \frac{M_{SAM,i} * (G_{EDF})_{aver}}{M_{SAM,} * (G_{EDF,i})}$$

or

$$WF_{E,i} = \frac{V_{SAM,i} * (V_{EDFW})_{aver}}{V_{SAM,} * (V_{EDFW,i})}$$

$i = 1,...n$

The value of the effective weighting factors shall be within ± 0.00
factors listed in ISO 8178-4.

APPENDIX C

ENVIRONMENTAL TRANSPORTATION CONSULTANTS CALCULATIONS

ETC CALCULATIONS
SOURCE TEST EQUATIONS

1. **Emission Rate, lb/hr**

from ppm data:
lb/hr = 8.223E-05 x (Q_s(std)) x (MW) x (ppm) / (T(std) + 460)

from gr/dscf data:
lb/hr = 0.00857 x (gr/dscf) x (Q_s(std))

from Heat Rate data:
lb/hr = (MMBtu/hr) x (lb/Btu)

2. **Emission Factor, lb/MMBtu**

from ppm data
lb/MMBtu = F-Factor x (MW) x [(1.3711E-06) / (T(std) + 460)] x (20.9 / 20.9 - %O_2) x (ppm)

from gr/dscf data
lb/MMBtu = F-Factor x 0.00014286 lb/grain x [20.9 / (20.9 - O_2 %)] x gr/dscf

3. **Emission Factor, lb/bbl**

lb/bbl = (lb/MMBtu) x (MMBtu / bbl)

4. **Emission Concentration**

dry, gr/dscf
gr/dscf = 15.432 x [Comp (g) / Vm(std)]

wet, gr/scf
gr/scf = 15.432 x [Comp (g) /(Vm(std) + Vw(std))]

CO_2 Corrected
gr/dscf @ %CO_2 correction = gr/dscf x (%CO_2 correction / %CO_2 measured)

5. **Gaseous Concentration, ppm**

ppm = [1.60982 x (T(std) + 460) x (mg comp)] / MW x ($V_{m,std}$)

ppm (wet) = ppm (dry) x (1 - Bws)

ppm @ %O_2 correction = ppm measured x (20.9 - %O_2 correction / 20.9 - %O_2 measured)

6. **F-Factor, dscf/MMBtu**

dscf/MBtu = 10E+06 x [3.64(%H) + 1.53(%C) + 0.57(%S) + 0.14(%N) - 0.46(%O_2)] / (Btu/lb) x [(T(std) + 460) / 528]

7. **Qs(std), dscfm**

from Qs, acfm (where Qs = vs x As x 60)
dscfm = Qs x (1 - Bws) x [(T(std) + 460) / (Ts + 460)] x (P(stack) / Pstd)

from heat input
dscfm = MMBtu/hr x [F-Factor x (20.9 / (20.9 - %O_2)) x (hr / 60 min)]

CO_2 Corrected
gr/dscf @ %CO_2 correction = gr/dscf x (%CO_2 correction / %CO_2 measured)

8. **Heat Input, MMBtu/hr**

from lb/hr fuel gas:
MMBtu/hr = (lb/hr fuel gas) x Btu/lb x MM / 1E+06

from ft^3/hr fuel gas:
MMBtu/hr = (ft^3 / hr fuel gas) x Btu/lb x (lb / ft^3 fuel gas) x MM / 1E+06

from lb/hr fuel oil:
MMBtu/hr = (lb/hr fuel oil) x Btu/lb x MM / 1E+06

from gal/hr fuel oil:
MMBtu/hr = (gal/hr fuel oil) x lb/gal x Btu/lb x MM / 1E+06

from lb/hr solid fuel:
MMBtu/hr = (lb/hr solid fuel) x Btu/lb x MM / 1E+06

9. **Heat Input, MMBtu/bbl**

MMBtu/bbl = 349.786E-6 (Btu/lb)(SpGr)

10. **Fuel Useage, MCF/hr**

from fuel gas:
MCF/hr = MMBtu/hr / (Btu/ft^3) x (1E+06/MM) x (M/1000)

11. **I.C. Engines**

Brake Specific Emission Rate, grams/brake horsepower hour
grams/hr = (lb/hr * 453.6/lb)

grams/BHP-hr = (grams/hr / BHP)

Particulate Calculations

Particulate Concentration (g./m^3) Net Sample Weight / Sample Volume

Particulate Mass Rate (lb/hr) g/m^3 * (m^3/minute) * 60 min. * 0.002205

Particulate Mass Rate (g/kWh) - lb/hr. * 453.592 / Kilowatts

Where:
0.002205 = conversion factor - grams to pounds.
453.592 = grams per pound
0.0283 = conversion factor dscfm to m^3/min (dry)
0.74558 = conversion factor horsepower to Kilowatts

Sample Volume reported in liters @ 68° F,and 29.92" hg standard conditions.

Exhaust Gas Flow Rate reported in units of cu. meters per minute @ 68°F and 29.92" hg standard conditions, these units were derived from fuel based calculations converted to m^3/min. using the factor 0.0283

APPENDIX D

MAR, Inc. DATA ANALYSIS

4 SHIP TEST RESULTS

4.1 Data Analysis

A number of different types of comparison test runs were made to determine the effect of engine loading on emissions. However, the same data was taken for all test runs. The method used to analyze these data is described in this section with the results of the analysis discussed in sections that follow. The procedures and nomenclature in ISO standard DP 8178-1, RIC Engines - Exhaust Emission Measurement, were followed in making calculations.

In some cases part of the data was missed due to instrumentation failures. However, sufficient data were collected to permit the missing data to be estimated based on a regression analysis on the data that was collected. A regression curve was fitted to the available data and this curve was used to estimate the value of missing parameters.

Because the intake air flow is generally not measured, the test protocol for shipboard testing envisioned using a carbon balance approach to determining the exhaust mass flow. The R&D Center was able to purchase an air flow measuring device adaptable to the caterpillar engines on the 82 ft WPBs. With air flow available, the data analysis was greatly simplified.

The following data were collected:

a. Barometric Pressure (Inches of mercury) {29.92" Hg = 101.33 kPa}
b. Relative Humidity near intake (percent)
c. Temperature associated with Relative Humidity (°F)
d. Intake Air Temperature (°F)
e. Shaft RPM
f. Engine RPM
g. Shaft Horsepower (Horsepower) {1 HP = 0.746 kw}
h. Fuel Flow Rate (U.S. gallons/hour) {1 gal = 0.0037854 m^3}
i. Intake Air Flow Rate (cubic feet/minute) {1 cu.ft. = 0.028313 m^3}
j. Stack Temperature (°F)
k. Oxygen volume (dry) in exhaust (percent)
l. CO volume (dry) in exhaust (ppm)
m. CO_2 volume (dry) in exhaust (percent)
n. Excess Air volume (dry) in exhaust (percent)
o. NO volume (dry) in exhaust (ppm)
P. NO_2 volume (dry) in exhaust (ppm)
q. NO_X volume (dry) in exhaust (ppm)

The following parameters were calculated based on the above data:

GFUEL - Fuel Mass Flow Rate (kg/hr)

GFUEL = 0.00379 x Fuel Flow Rate (gal/hr) x Fuel Density (kg/m^3)

Fuel Density = 833 kg/m^3 for the diesel fuel used.

GAIRD - Dry Air Mass Flow Rate (kg/hr)

GAIRD = 1.698 x Intake Air Flow Rate (ft^3/min) x Dry Air Density (kg/m^3)

Where the coefficient changes units of volume and time.

A Psychrometric chart for a pressure of 30.00" Hg was used to determine the air density at the measured relative humidity and temperature.

GH2O - Water Mass Flow Rate (kg/hr)

GH2O = 1.698 x Intake Air Flow Rate x Absolute Humidity x Dry Air Density

Where Intake Air Flow Rate is in ft^3/min,
Absolute Humidity is in (kg H_2O)/(kg Dry Air), and
Dry Air Density is in kg/m^3.

A Psychrometric chart for a pressure of 30.00" Hg was used to determine the absolute humidity and air density at the measured relative humidity and temperature.

GEXHW - Exhaust Mass Flow Rate (Wet) (kg/hr)

GEXHW = GFUEL + GAIRD + GH2O

FFH - Fuel Specific Factor representing the hydrogen to carbon ratio

FFH was taken from Table (9) in ISO/DP 8178-1 for diesel fuel based on the excess air measured in the exhaust. Factor has a range of 1.783 - 1.920. This factor is used to correct the dry concentrations of measured gases to wet concentrations.

KW - Dry to Wet correction factor

$$KW = \left(1 - FFH \times \frac{GFUEL}{GAIRD} \right) - KW2$$

$$\text{Where } KW2 = \frac{1.608 \times \text{Absolute Humidity (g/kg)}}{1000 + \text{Absolute Humidity (g/kg)}}$$

$$\text{Concentration(wet)} = KW \times \text{Concentration(dry)}$$

Gas Mass Flow Rate (grams/Hour)

Exhaust gas flow rates measured in ppm or percent are by volume. These need to be converted to a mass basis.

Gas Mass Flow Rate = u x Concentration(wet) x GEXHW

Where u is in grams of gas/kg of exhaust,
Concentration(wet) is in ppm or percent, and
GEXHW is in kg/hr

$$u = \frac{4.4615 \times 10^{-5}\ (\text{Mol/m}^3) \times \text{Molecular Weight (g/Mol)}}{\rho_{air}\ (\text{kg/m}^3)} \quad \text{for concentrations in ppm}$$

ρ_{air} = 1.293 kg/m^3 at 0 °C and 101.33 kPa pressure

Power (kw) = Shaft Horsepower x 0.746 (kw/HP)

Emissions (g/kw-hr) = Gas Mass Flow Rate (g/hr)/Power (kw)

Emissions (kg/tonne fuel) = Gas Mass Flow Rate (kg/hr)/GFUEL (metric tons/hr)

NO/NOx = Volume ratio (dry)

O_2 Weight Fraction = Wet O_2 (kg/hr)/GEXHW (kg/hr)

4.2 USCGC POINT FRANCIS

The USCGC POINT FRANCIS which operates out of New London, CT, was tested on the 13th and 16th of August 1993. Tests consisted of free running tests with and against the current, and a shallow water and deep water comparison. However, the shallow water runs were conducted in approximately 30 feet of water which creates very little extra loading for a boat of the 82 ft WPB's size. The deep water runs were made in approximately 120 feet of water. No acceleration/deceleration runs were conducted on the POINT FRANCIS or on the other two cutters tested because of problems with continuous data recording with the test instrumentation used.

APPENDIX E

VNTSC - SOURCES USED FOR LITERATURE SEARCH

VNTSC - SOURCES USED FOR LITERATURE SEARCH

The following is a log of sources and list of pertinent reports that have been investigated to date:

Abbott, James, editor, "Jane's World Railways", 1994-95, Jane's Information Group Limited, Surrey, United Kingdom, 1994.

Barris, Marty A., "Development of Diesel Exhaust Catalytic Converter Mufflers", No. 920369, "Diesel Particulate Control, Trap, and Filtration Systems", Society of Automotive Engineers, Inc., SP-896, Warrendale, PA, February 1992, pp. 167.

Code of Federal Regulations, 40 CFR Part 89.

Compendex Plus™, Dialog OnDisk, 1994-1992.

Environmental Transportation Consultants, Volpe National Transportation Systems Center and United States Coast Guard Headquarters Naval Engineering Division, "Shipboard Marine Engines Emission Testing for The United States Coast Guard", Final Report, Delivery Order No. 31, pp. 10-1 to 10-4.

Environmental Transportation Consultants, Volpe National Transportation Systems Center and United States Coast Guard Headquarters Naval Engineering Division, "United States Coast Guard Marine Diesel and Gas Turbine Air Emissions Survey: Fleet Profile Survey Data", March 1995.

Federal Register, Vol. 59 No. 216 Wednesday, November 9, 1994, p.55930 (proposed rule), Environmental Protection Agency, 40 CFR Parts 89 and 91, "Control of Air Pollution; Emissions Standards for New Gasoline Spark-ignition and Diesel Compression-ignition Marine Engines".

Gulati, Saresh T., "Design Considerations for Diesel Flow-Through Converters", No. 920145, "Diesel Particulate Control, Trap, and Filtration Systems", Society of Automotive Engineers, Inc., SP-896, Warrendale, PA, February 1992, pp. 89.

Harayama, Naoya, and Keiichi Niimura, Yoshito Watanabe, "Effects of Sulfate Adsorption on Performance of Diesel Oxidation Catalysts", No. 920852, "Diesel Particulate Control, Trap, and Filtration Systems", Society of Automotive Engineers, Inc., SP-896, Warrendale, PA, February 1992, pp. 257.

Heywood, John B., Internal Combustion Engine Fundamentals, McGraw-Hill, Inc., New York, 1988.

Hug, H. T. and A. Mayer, A. Hartenstein, "Off-Highway Exhaust Gas After-Treatment: Combining Urea-SCR, Oxidation Catalysis and Traps", No. 930363, "Diesel Exhaust

Aftertreatment", Society of Automotive Engineers, Inc., SP-943, Warrendale, PA, March 1993, pp. 143.

Jane's Publishing Company Limited, "Jane's High-Speed Marine Craft And Air Cushion Vehicles 1987", London, England.

Jane's Publishing Company Limited, "Jane's Fighting Ships 1987-88", London, England, 1988.

Khair, Magdi K., and Bruce B. Bykowski, Southwest Research Institute, San Antonio, Texas, "Design and Development of Catalytic Converters for Diesels", SAE Paper No. 921677, SAE International, Warrendale, PA.

Kong, Song-Charng, and Laura M. Ricart, Rolf D. Reitz, "In-Cylinder Diesel Flame Imaging Compared with Numerical Computations", SAE Paper No. 950455, SAE International, Warrendale, PA.

Ladommatos, N. and S. M. Abdelhalim, H. Zhao, Z. Hu, SAE Technical Paper Series No. 961165, "The Dilution, Chemical, and Thermal Effects of Exhaust Gas Recirculation on Diesel Engine Emissions - Part 1: Effect of Reducing Inlet Charge Oxygen", International Spring Fuels & Lubricants Meeting, Dearborn, Michigan, May 6-8, 1996, SAE International, Warrendale, PA.

Loscutoff, Walter V. and Dennis Hooper, James E. Ettaro, prepared for California Energy Commission, "Feasibility Study of Using Water Injection to Reduce Exhaust Emissions on Diesel Engines", June 1995, Engineering Research Institute, California State University at Fresno, Fresno, California.

McDonald, J. F. and D. L. Purcell, B. T. McClure, D. B. Kittelson, SAE Technical Paper Series No. 950400, "Emissions Characteristics of Soy Methyl Ester Fuels in an IDI Compression Ignition Engine", SAE International, Warrendale, PA.

Miyamoto, Noboru and Hideyuki Ogawa, Jianxin Wang, Kenji Yamazaki, SAE Technical Paper Series No. 961164, "Simultaneous Reductions in Diesel NOx and Smoke Emissions with Aqueous Metal-Salt Solutions Directly Injected into the Combustion Chamber", International Spring Fuels & Lubricants Meeting, Dearborn, Michigan, May 6-8, 1996, SAE International, Warrendale, PA.

National Technical Information Service (NTIS), Dialog OnDisk 1985-1989.

Odaka, Matsuo, and Noriyuki Koike, Yujiro Tsukamoto, Kazuyuki Narusawa, Koichi Yoshida, SAE Technical Paper Series No. 910739, "Effects of EGR with a Supplemental Manifold Water Injection to Control Exhaust Emissions from Heavy-Duty Diesel Powered Vehicles", International Congress and Exposition, Detroit, Michigan, February 25-March 1, 1991, SAE International, Warrendale, PA.

Odaka, Matsuo, and Noriyuki Koike, Yujiro Tsukamoto, Kazuyuki Narusawa, SAE Technical Paper Series No. 920468, "Optimizing Control of NOx and Smoke Emissions from DI Engine

with EGR and Methanol Fumigation", International Congress and Exposition, Detroit, Michigan, February 24-28, 1992, SAE International, Warrendale, PA.

Osenga, Mike, Diesel Progress: Engines & Drives, "Emissions/Alternative Fuels: Special Report" "The Fuel of the Future? Caterpillar Taking Close Look At A-21 As Diesel Fuel Alternative", p.90-92, June 1996

Pierpont, D. A. and D. T. Montgomery, R. D. Reitz, "Reducing Particulate and NOx Using Multiple Injections and EGR in a D.I. Diesel", SAE Paper No. 950217, SAE International, Warrendale, PA.

Quandt, Earl, "European Technology for Reducing Exhaust Pollution from Naval Ship Engines", Naval Surface Warfare Center, Carderock Division, NSWCCD-TR-80-96/02, April 1996, Bethesda, MD.

Satoshi, Kato, and Shigeru Onishi, G. Takeshi Sato, Hideaki Tanabe, "Development of Low NOx Emission Diesel Engine by Impingement of Fuel Jet", SAE Paper No. 921645, SAE International, Warrendale, PA.

Stumpp, Gerhard and Wilhelm Polach, N. Muller, J. Warga, SAE Technical Paper Series No. 890851, "Fuel Injection Equipment for Heavy Duty Diesel Engines for U. S. 1991/1994 Emission Limits", International Congress and Exposition, Detroit, Michigan, February 27-March 3, 1989, SAE International, Warrendale, PA.

Sumiya, S. and G. Muramatsu, N. Matsumura, K. Yoshida, R. Schenck, "Catalytic Reduction of NOx and Diesel Exhaust", No. 920853, "Diesel Particulate Control, Trap, and Filtration Systems", Society of Automotive Engineers, Inc., SP-896, Warrendale, PA, February 1992, pp. 263.

Southwest Research Institute, "Diesel Fuel Specification and Locomotive Improvement Program, Tenth Research Phase, Final Report", Prepared for The Association of American Railroads, AAR Report No. R-771, December 1989, San Antonio, Texas.

Southwest Research Institute, "Locomotive Improvement Program, Eleventh Research Phase, Final Report", Prepared for The Association of American Railroads, AAR Report No. R-807, December 1990, San Antonio, Texas.

Southwest Research Institute, "Locomotive Improvement Program, Twelfth Research Phase, Final Report", Prepared for The Association of American Railroads, AAR Report No. R-841, July 1993, San Antonio, Texas.

Southwest Research Institute, "Locomotive Exhaust Emission Field Tests, Phase I, Final Report", Prepared for The Association of American Railroads, AAR Report No. R-877, October 1994, San Antonio, Texas.

Southwest Research Institute, "Locomotive Exhaust Emission Field Tests, Phase II", Prepared for The Association of American Railroads, AAR Report No. R-885, March 1995, San Antonio, Texas.

Takeda, Yoshinaka and Nakagome Keiichi, Niimura Keiichi, SAE Technical Paper Series No. 961163, "Emission Characteristics of Premixed Lean Diesel Combustion with Extremely Early Staged Fuel Injection", International Spring Fuels & Lubricants Meeting, Dearborn, Michigan, May 6-8, 1996, SAE International, Warrendale, PA.

The 1993 WorkBoat Diesel Engine Directory

Uchida, Noboru, and Yasuhiro Daisho, Takeshi Saito, Hideaki Sugano, SAE Technical Paper Series No. 930601, "Combined Effects of EGR and Supercharging on Diesel Combustion and Emissions", International Congress and Exposition, Detroit, Michigan, March 1-5, 1993, SAE International, Warrendale, PA.

Weaver, Christopher S. and Douglas B. McGregor, "Emissions Control Technology for Locomotive Engines", SAE Paper No. 940453, Diesel Exhaust Aftertreatment 1994, SP-1020, SAE International, Warrendale, PA, February 1994.

World Wide Web:

http://www.sae.org/CALENDAR/tecfl96.htm
http://www.usbm.gov/hs/altfuel.html
http://158.132.54.75/IMO.htm
http://158.132.54.75/IMLA/AcqList/AcqList.htm
http://www.detdiesel.com/10kprodc.htm
http://www.cummins.com/
http://tardis.union.edu/community/project95/ALCO/history.html
http://www.engelhard.com/MNI.html
http://www.history.rochester.edu/fmed/